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Hydrology and Freshwater Ecology

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EXECUTIVE SUMMARY

The hydrological system is potentially very sensitive to changes in climate. Changes in precipitation affect the magnitude and timing of runoff and the frequency and intensity of floods and droughts; changes in temperature result in changes in evapotranspiration, soil moisture, and infiltration. The resulting changes in surface wetness, reflectivity, and vegetation affect evapotranspiration and the formation of clouds, as well as surface net radiation and precipitation. Meanwhile, the hydrological system is being affected by other, more direct human activities, such as deforestation, urbanization, and water-resource exploitation.

The effects of climate change on hydrological regimes are generally estimated by combining catchment-scale hydrological models with climate change scenarios derived from general circulation model (GCM) output. In addition to the uncertainties associated with GCM simulations, there are three major problems in estimating the hydrological effects of climate change: (1) expressing scenarios at a scale appropriate for hydrological modeling; (2) the considerable errors inherent in climatic and hydrological data used to validate hydrological models; and (3) converting climatic inputs into hydrological responses. Methods have been developed to address most of these problems, but estimates of the hydrological effects of climate change remain very uncertain. This uncertainty is largely due to difficulties in defining credible scenarios for changes in precipitation and assessing vegetation response to a changed atmosphere at appropriate spatial scales.

There are considerable differences in estimated changes in hydrological behavior both between scenarios and between catchments, but it is possible to draw some general conclusions about sensitivities:

- We have a high level of confidence that an increase in air temperature would increase potential evapotranspiration, but the magnitude of increase depends also on changes in net radiation, humidity, windspeed, precipitation and its temporal distribution, and vegetation characteristics. Actual evapotranspiration may increase or decrease according to the availability of soil moisture.
- The effect of a given change in precipitation and evapotranspiration on river runoff and groundwater recharge varies considerably between catchments, depending on climatic regime and (at shorter time scales) catchment physical characteristics. We have a high level of confidence that, in general, the drier the climate, the greater the sensitivity of hydrological regimes to changes in climate.
- Neither climatic nor hydrological change will be equally distributed throughout the year; in some cases it appears that the variability of river flow through the year would increase if climate were to change, and the frequency of both high and low flows would increase. We have a medium level of confidence in this finding, due to variations between catchments and scenarios.
- We have a medium level of confidence that more intense rainfall would tend to increase the occurrence of floods, although the magnitude of this effect would depend not only on the change in rainfall but also on catchment physical and biologic characteristics. These characteristics also may change due to human activity that may or may not be in response to climate change.
- An increase in the duration of dry spells would not necessarily lead to an increase in the occurrence of low river flows and groundwater levels. River flows may be sustained by increased precipitation earlier in the year. The effect of a change in the duration of dry spells depends significantly on catchment physical and biologic characteristics. We have a medium level of confidence in these findings.
- Hydrological regimes in many continental and mountain areas are determined by winter snowfall and spring snowmelt; if climate were to change and the proportion of precipitation falling as snow decreased, we have a high degree of confidence that in such regions there would be a widespread shift from spring to winter runoff. This effect may be modified by changes in the seasonal distribution and amounts of precipitation.
- Very little is known about possible changes in groundwater recharge, which will depend on the balance between changes in opportunities for recharge and the amount of water available for recharge. Therefore, we have a low level of confidence in any conclusions about or projections of changes in groundwater recharge.

Freshwater ecosystems, including lakes and streams (covered in this chapter) and noncoastal wetlands (see Chapter 6), are scattered across the landscape and tightly linked to regional hydrology. The effects of climate change on freshwater ecology will interact strongly with other anthropogenic changes in land use, waste disposal, and water extraction. Changes in lake and stream ecosystems will occur in the context of existing climates and expected changes; effects will differ greatly from place to place. General conclusions follow:

- We have a high level of confidence that climate change will influence freshwater ecosystems directly

through changes in water availability by altered flood regimes, water levels, and, in the extreme, the absence of water in streambeds and lake basins.

- We have a high level of confidence that changes in water temperature and thermal structure of freshwaters directly affect the survival, reproduction, and growth of organisms; productivity of ecosystems; persistence and diversity of species; and regional distribution of biota.
- We have a high level of confidence that changes in runoff, groundwater inputs, and direct precipitation to lakes and streams will alter the input of nutrients and dissolved organic carbon, which in turn will alter productivity and clarity. Changes in the duration of lake and stream ice and snow on ice will change mixing patterns, oxygen availability, and the survival and reproductive success of certain organisms.
- We have a medium level of confidence that increases in terrestrial productivity will enhance the productivity of streams by increasing the input of organic detritus and likely increasing the export of CO_2 from lakes to the atmosphere.
- We have a medium level of confidence that climate-induced changes in temperature, ice and snow cover, and biological production will be more intense at higher latitudes—where temperature changes are expected to be greatest—and at the lower-latitude edges of the geographic ranges of many taxa—where extinctions and extirpations will be the greatest, especially where isolation prevents the poleward dispersal of organisms in rivers and streams.
- We have a high level of confidence that water-level declines will be most severe in lakes and streams in dry evaporative drainages and in basins with small catchments—where in many years evapotranspiration losses already exceed precipitation and inputs from groundwater plus overland flow.
- We have a high level of confidence that the effects of an increase in severe flood events may be more damaging in drier climates where soils are more erodible and precipitation-runoff relationships are highly nonlinear. Drought events may be more severe in humid areas that have not experienced frequent droughts in the past.
- We have a high level of confidence that climate changes that increase variability are expected to have greater ecological effects than climate changes associated with a change in average conditions; increased variability in hydrologic conditions with associated flash floods and droughts will reduce the biological diversity and productivity of stream ecosystems.
- We have a high level of confidence that assemblages of organisms will tend to move poleward with warming, with range constrictions and local and global species extinctions occurring at the lower latitudes of their distributions and range extensions and invasions occurring poleward. For smaller, more hydrologically isolated basins, dispersal will lag considerably behind the warming in climate—resulting in near-term reductions in diversity.
- We can say with a lower degree of confidence that warming of larger and deeper temperate lakes may increase their productivity, provided that nutrient inputs are not greatly reduced; in some shallow, stratified lakes, this increase in productivity would lead to a greater likelihood of anoxic conditions in deep water, with subsequent loss of cold-water fauna.
- We have a medium level of confidence that changes in vegetation, in rainfall, and in hydrological regimes affect erosion on hillslopes and in river channels, sedimentation, and channel stability.

Water quality will be affected by changes in water temperature, CO_2 concentration, the processes by which water gets into the stream network and aquifers, and the timing and volume of streamflow. The relative importance of these influences varies between catchments and chemical species, and the influences interact to ameliorate or exaggerate the effects of change. Dissolved oxygen concentrations would not change much if higher water temperatures were associated with increased streamflow, but if streamflow were to decline there would be a large decrease in dissolved oxygen concentrations. In many catchments, stream and groundwater quality is determined by human influences—such as the application of agricultural chemicals, urbanization, and the return of treated sewage. The water quality of streams that already are polluted is likely to be affected by changes in temperature and flow regimes, but changes in land use and the input of pollutants may have a far greater effect than changes in climate.

10.1. Introduction

The hydrological cycle and the climate system are intimately linked. Any change in climate is reflected in changes in key hydroclimatic elements of the hydrological cycle and vice versa: Changes in precipitation affect the magnitude and timing of runoff and groundwater recharge, as well as the frequency and intensity of floods and droughts; changes in temperature result in changes in evapotranspiration, soil moisture, and infiltration conditions, with resulting changes in surface wetness, reflectivity, and vegetation that affect evaporation and the formation of clouds, as well as surface net radiation and—completing the cycle—precipitation.

Freshwater ecosystems include lakes, streams, and wetlands scattered across the landscape and are tightly linked to regional hydrology. These surface freshwater systems constitute a set of scarce resources for humans sensitive to climate change; excluding ice, they constitute only 0.009% of the volume of water on Earth (Goldman and Horne, 1983). Of these surface freshwaters, 99% (by volume) are lakes and 1% are streams. Groundwater is 66 times more abundant than surface freshwaters but still represents only 0.6% of the volume of all surface waters. Freshwater systems greatly influence the distribution of populations and economic growth, add greatly to the biological and ecological diversity of the landscape, and provide a variety of goods and services. The effects of climate change on freshwater ecosystems will interact strongly with anthropogenic changes in land use, waste disposal, and water extraction.

This chapter examines the sensitivities of hydrological and freshwater systems to climate change. The chapter covers four main issues: (1) the potential effects of global warming on components of the hydrological cycle; (2) possible changes in the frequency and magnitude of extreme high and low flows; (3) implications for thermal, chemical, and morphological changes; and (4) consequences for stream and lake ecosystems. The consequences of changes in freshwater systems affecting water resources, ecosystem management, agriculture, power production, and navigation are examined in other chapters of this report.

Although some of the principal linkages between climate and the hydrological system are well understood, predicting the effects of global warming is very uncertain. Current general circulation models (GCMs) work at a spatial resolution that is too coarse for hydrological purposes, producing weather averaged over too large a geographic area and producing average conditions rather than changes in ranges, frequencies, seasonal distributions, and so forth. They do not yet include all of the relevant feedbacks between the land surface and the atmosphere. There is considerable uncertainty in the translation of climate changes into hydrological effects through hydrological models and an inability to maintain consistency between GCM and hydrological model water balances, particularly for evaporation. Different models give different sensitivities to change, and a model calibrated under current conditions may not be appropriate under a changed climate. There still are major uncertainties over the effects of increased CO_2 concentrations on plant water use—and hence transpiration rates—in natural settings at the catchment scale.

Because of the spatial complexity of the Earth's climate-water system, there is no ideal method to delineate hydroclimatic regions that could be used in this chapter. The case studies selected cover all the world's main climatic belts as used by L'vovich (1979)—subpolar, temperate, subtropical, tropical, equatorial, and mountain regions—taking into account the degree of climatic aridity and humidity in the regions covered by the study. The literature available does not cover all regions adequately, and major gaps remain in the regional coverage of published studies and the quality of the data.

10.2. The Hydrological Cycle

10.2.1. The Hydrological Cycle in the Climate System

The hydrological cycle is driven by solar energy and involves water changing its form through the oceans, atmosphere, land and vegetation, and ice and glaciers. After precipitation water reaches the Earth's surface, it either remains on the surface as rain or snow; quickly evaporates; infiltrates into the soil, where it is taken up by vegetation (and eventually transpired through photosynthesis and respiration); moves along the surface or through the soil toward rivers and streams; or percolates to aquifers, recharging groundwater and subsequently draining into rivers and oceans, perhaps after delays of years or centuries. Some water is stored over the winter as snow and over longer time scales as ice.

The partitioning of incoming precipitation between storage, evaporation, infiltration, groundwater recharge, and runoff varies widely between catchments, depending on climatic and catchment characteristics. Vegetation cover has a major effect on the water and energy balance, particularly through interception and evaporation. There are many types of hydrological regimes with different combinations of processes, but it helps to distinguish among three major types: snow-dominated, humid, and semi-arid/arid. In the first regime, a significant proportion of precipitation falls as snow and is stored on the surface until it melts during the spring. In a humid regime, rainfall infiltrates into the soil and reaches the stream network by a variety of routes over different time scales. In semi-arid and arid environments, rainfall is short-lived and generally very intense, and soils tend to be thin. A large proportion of rainfall therefore runs directly off the surface, only to infiltrate into deeper soils downslope or along the river bed.

Hydrological responses vary over time scales from seconds, to days or weeks, through years to decades, and have continuous feedbacks with the atmosphere. In the most general terms, the amount of water present at and beneath the surface affects both the proportion of incoming energy reflected back into the atmosphere and the partitioning of the remaining net radiation between sensible and latent heat. A change in the land surface, and in the hydrological processes operating at the surface, therefore will affect atmospheric processes; the magnitude of the effect depends on the degree and extent of change, as well as local climatic characteristics. It is increasingly clear that hydrological variability can be interpreted in terms of large-scale climatic anomalies—such as those associated with the El Nino/Southern Oscillation (ENSO)—and that there are strong relationships between hydrological anomalies in different parts of the world (e.g., Redmond and Koch, 1991; Aguado *et al*., 1992; Mechoso and Iribarren, 1992; Simpson *et al*., 1993; Dracup and Kahya, 1994; Ely *et al*., 1994).

10.2.2. Anthropogenic Non-Climatic Impacts on the Hydrological Cycle

Human activities are interfering with the hydrological cycle in many regions and catchments. There are many different types of impact; they can be deliberate (perhaps with unanticipated consequences) or inadvertent, and they affect the quantity and quality of water and aquatic biota. Such activities include:

- **River impoundment and regulation**: Dams for flood protection, hydropower purposes, or inland navigation and related control measures generally cause changes in the spatial and temporal distribution of streamflow, which also may have impacts on evaporation and infiltration in areas close to the river bed, as well as on biota. Of particular importance are increases or decreases in river infiltration to groundwater aquifers.
- **Impacts of land use and land-use changes**: Anthropogenic activities that affect the land surface include urbanization; agricultural activities such as irrigation, drainage, land improvement, and the application of agricultural chemicals; deforestation and afforestation; and overgrazing. These activities can cause locally and regionally significant changes in evaporation, water balance, flood and drought frequency, surface and groundwater quantity and quality, and groundwater recharge.
- **Water removal and effluent return**: Water used for municipal, industrial, and agricultural purposes can affect river flows and groundwater levels. This water may subsequently be returned to the hydrological system (although much water used for irrigation is lost by evaporation), but at a lower quality.
- **Large-scale river diversions**: Large-scale diversions of river flow or parts of it, mainly for purposes of irrigation or hydropower generation, can cause serious and manifold changes in the ecosystems of large areas.

10.2.3. Methods for Estimating the Hydrological Effects of Climate Change

There are several possible ways of creating scenarios for climate-change impact studies. Temporal analogs (e.g., Krasovskaia and Gottschalk, 1992) use the past as an analog for the future; spatial analogs substitute one location for another. Many studies have examined the effect of arbitrary changes in climatic inputs on the hydrological system (e.g., Novaki, 1992a, 1992b; Gauzer, 1993; Chiew *et al*., 1995). Although most studies now use scenarios based on GCM simulations, there is a multitude of uncertainties associated with their use—which are listed here by their relative importance (the first being the most critical):

- Weaknesses of models in coupling the land surface and atmospheric hydrologic cycles and in GCM simulations of regional climate and extremes, particularly with regard to precipitation
- Weaknesses in using GCM simulations to define climate-change scenarios at the spatial and temporal scales required by hydrological models. The spatial resolution of current GCMs is too coarse for their output to be fed directly into hydrological models.
- Weaknesses in simulating changes in hydrological characteristics with given changes in climatic inputs to the hydrological system, which reflect difficulties in developing credible hydrological models with sparse and error-contaminated climatic and hydrological data.

Figure 10-1 attempts to summarize the relative magnitude of the uncertainties. Given that a reasonably realistic hydrological model is used, the greatest uncertainty in hydrological climate-change impact assessment lies in the initial scenarios derived from GCMs—which do not include all of the relevant feedbacks between the land surface and the atmosphere—and the derivation of catchment-scale climate scenarios. Sections 10.2.3.1 through 10.2.3.3 explore further the stages in this cascade of uncertainties.

10.2.3.1. GCMs and Hydrological Requirements

GCMs show progress in simulating the present climate with respect to annual or seasonal averages at large spatial scales (>10^4 km^2) but perform poorly at the fine temporal and spatial scales

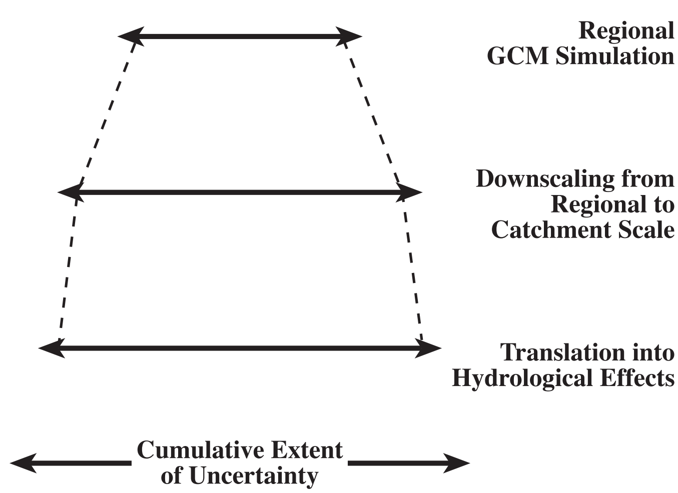

Figure 10-1: Uncertainties in hydrological impact assessment.

relevant to hydrological studies (Askew, 1991; Grotch and MacCracken, 1991). Although GCMs are unanimous in their projections that a doubling of current atmospheric CO_2 concentrations would lead to an increase in global mean temperature and precipitation, they differ in their projections of changes in temperature and precipitation at regional scales that are the same order of magnitude as projected global changes. The direct use of GCM output to drive hydrological models is considered inappropriate due to the coarse resolution of the spatial grids used by current GCMs (relative to the scale of river basins); the simplified GCM representations of topography, land surface and cloud processes, and energy transfer within the oceans; and the simplified coupling of the atmosphere and the oceans. Until recent GCM transient runs, GCM simulations usually were of short duration (less than 30 years) and may not have captured the extreme events of particular interest in flood and drought analyses.

From a hydrological perspective, there is a need to improve the representation of land-surface processes and their interaction with the atmosphere. There now are intensive field studies into the interaction between land-surface hydrological processes and climate at point and regional scales (e.g., HAPEX-MOBILHY: Andre *et al*., 1986; HAPEX-SAHEL: Goutorbe *et al*., 1993; EFEDA: Bolle *et al*., 1993), as well as work to improve models of land-surface processes (e.g., Wood *et al*., 1992). The World Climate Research Programme (WCRP) sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of UNESCO, and the International Council of Scientific Unions has launched a Global Energy and Water Cycle Experiment (GEWEX). The GEWEX Continental-Scale International Project (GCIP) is an initiative to study the water and energy budgets of an extensive geographical area with a large volume of accessible data; the Mississippi River basin has been selected as the primary region of interest. Similar projects have been organized in other areas of the world—such as the Baltic Sea region (BALTEX), the boreal region (BOREAS), and the Himalaya/monsoon region (GAME).

Changes in the temporal distribution of precipitation—even with average precipitation remaining stable—may result in changes in river flow and its extremes, floods and droughts, and water availability for plants and water supply. There is a need to consider changes to the statistical distributions of weather variables rather than just their means because changes in response to climatic warming may be reflected more in extreme events than in average conditions (Katz and Brown, 1992).

10.2.3.2. Creating Scenarios at the Hydrological Scale

GCMs operate at a spatial scale far coarser than hydrological models and do not necessarily simulate regional-scale climate particularly well. It is therefore necessary to downscale GCM results to the catchment scale. Several techniques have been developed to derive scenarios at this spatial scale from GCM output:

- Direct use of GCM-simulated changes in precipitation, temperature, and evaporation, perhaps interpolated to the catchment scale and applied to observed catchment climate data (e.g., Bultot *et al*., 1992; Arnell and Reynard, 1993; Viner and Hulme, 1994; Kirshen and Fennessey, 1995)
- Stochastic generation of point-scale weather, with stochastic model parameters adjusted according to scenarios derived from GCM output (e.g., Nathan *et al*., 1988; Cole *et al*., 1991; Wilks, 1992; Wolock *et al*., 1993; Bates *et al*., 1994, 1995; Valdés *et al*., 1994; Rao and Al-Wagdany, 1995; Tung and Haith, 1995)
- Estimation of catchment-scale weather from large-scale climatic features, such as weather types and mean sea-level pressure fields (e.g., Bardossy and Plate, 1992; Hay *et al*., 1992; Hughes *et al*., 1993; von Storch *et al*., 1993)
- Use of nested regional limited-area models embedded within GCMs to simulate regional climate at a higher spatial resolution (e.g., Leavesley *et al*., 1992; Hostetler and Giorgi, 1993; McGregor and Walsh, 1994).

10.2.3.3. Hydrological Modeling and Impact Assessment

Hydrological models have been used to a large extent to determine the relative sensitivity of hydrological variables to climatic inputs. These simulations have been useful in the search for amplification effects—that is, whether small changes in one (climatic) variable may cause substantial changes in another variable, thus aggravating water problems particularly in areas that are presently vulnerable. Such a sensitivity analysis allows assessment of the impact of the relative increase or change in temperature and precipitation on changes in hydrological variables of interest (e.g., runoff, evapotranspiration, soil moisture, flood potential). Results of sensitivity analyses are useful in practical "what-if" considerations. Sensitivity analyses also underscore uncertainty in the prediction of future water resources. They may include inconsistencies by ignoring other important climatic variables that may be affected by climate change, such as net radiation, wind, and humidity.

Current approaches to hydrological modeling for climate-change impact assessment include empirical models, water-balance models, conceptual rainfall-runoff models, and physically based, distributed models (Leavesley, 1994). Empirical models consider statistical relations between annual runoff and precipitation, temperature, or potential or actual evapotranspiration for present-day conditions (Revelle and Waggoner, 1983; Arnell, 1992; Duell, 1994). Runoff under changed climate conditions is obtained from regression models by perturbing historical climate series. This approach assumes that the functional form as well as the parameters of a regression model remain valid for a changed climate. Leavesley (1994) has questioned the validity of this approach, and Arnell (1992) has shown that it should be used with extreme caution because the estimated sensitivities to change are very dependent on details of the model. Water-balance and conceptual rainfall-runoff models simulate the movement of water from the time it enters a catchment as precipitation to the time it leaves the catchment as runoff, although rainfall-runoff models consider the flow paths and residence times of water in finer detail (Leavesley, 1994). Klemes (1985) and Becker and Serban (1990) state that calibrated water-balance or conceptual rainfall-runoff models are not directly usable for assessing climate-change impacts because the model parameter estimates are assumed to remain valid for the changed climate. This point was illustrated by Gan and Burges (1990), who found that the calibrated sizes of conceptual moisture storages are not climate-invariant. The size of this problem can be checked, at least approximately, by comparing model prediction errors based on parameters estimated from wet and dry periods within historical records. Physically based models appear to be a superior alternative because their parameters are estimated from field measurements or physically based analyses. These models use physically based process equations to simulate the spatial variability of runoff due to spatial variations in land characteristics such as soil type and topography, as well as rainfall. Although physically based models have the potential to become a universally applicable tool, they come with the price of increased model complexity, data requirements, and computing costs. In practice, there is a paucity of measured field data and a lack of methods for the collection of data at a scale appropriate for such models, limiting their application to studies of small-catchment hydrology (Grayson *et al*., 1992a, 1992b).

The development of a large-scale model of land-surface hydrology may be started from an even larger-scale continuum of atmospheric processes, which is how GCM researchers were proceeding until recently. In this approach, it is necessary to simplify the spatial distribution of variables of the land surface to an extent that not only distorts their physical significance but provides spatially imprecise inputs to the atmospheric models at the land-atmosphere interface. This problem has been identified by GCM researchers in studies of the regional aspects of changes in climatic variables. Another way to solve the problem is to develop a macroscale model, starting from mesoscale analysis of hydrological processes, as practiced by hydrologists in simulations for water resources management purposes. Although the call for such an approach is being heard more and more frequently, a model of this type is not yet available.

Large-scale hydrological models, which estimate vertical fluxes of the land-surface/atmosphere interface and horizontal fluxes resulting in measurable runoff, using physically based parameters, could be very important in assessing the impacts of climate change and could improve GCM regional simulations through inputs to GCM hydrology. Additional sources of information on these topics include a recent discussion on the type and use of scenarios and hydrological models by Lettenmaier *et al*. (1994), a review of research on climate-change impact on water resources by Chang *et al*. (1992), and the Proceedings of the First National Conference on Climate Change and Water Resources Management (Ballentine and Stakhiv, 1993).

10.3. Effects of Climate Change on the Hydrological Cycle

10.3.1. Introduction

The complex and interacting effects of an increasing concentration of greenhouse gases on the hydrological system are shown in Figure 10-2 (Arnell, 1994). The increase in greenhouse gas concentrations results in an increase in net radiation at the Earth's surface, which results in changes in temperature, rainfall, and evaporation—and hence soil moisture regimes, groundwater recharge, and runoff. Temperature, rainfall, evaporation, and soil moisture affect vegetation growth, as do changes in incoming solar radiation and the atmospheric CO_2 concentration. Higher CO_2 concentrations also may affect plant water use (see Chapter 9*, Terrestrial Biotic Responses to Environmental Change and Feedbacks to Climate*, of the Working Group I volume). The

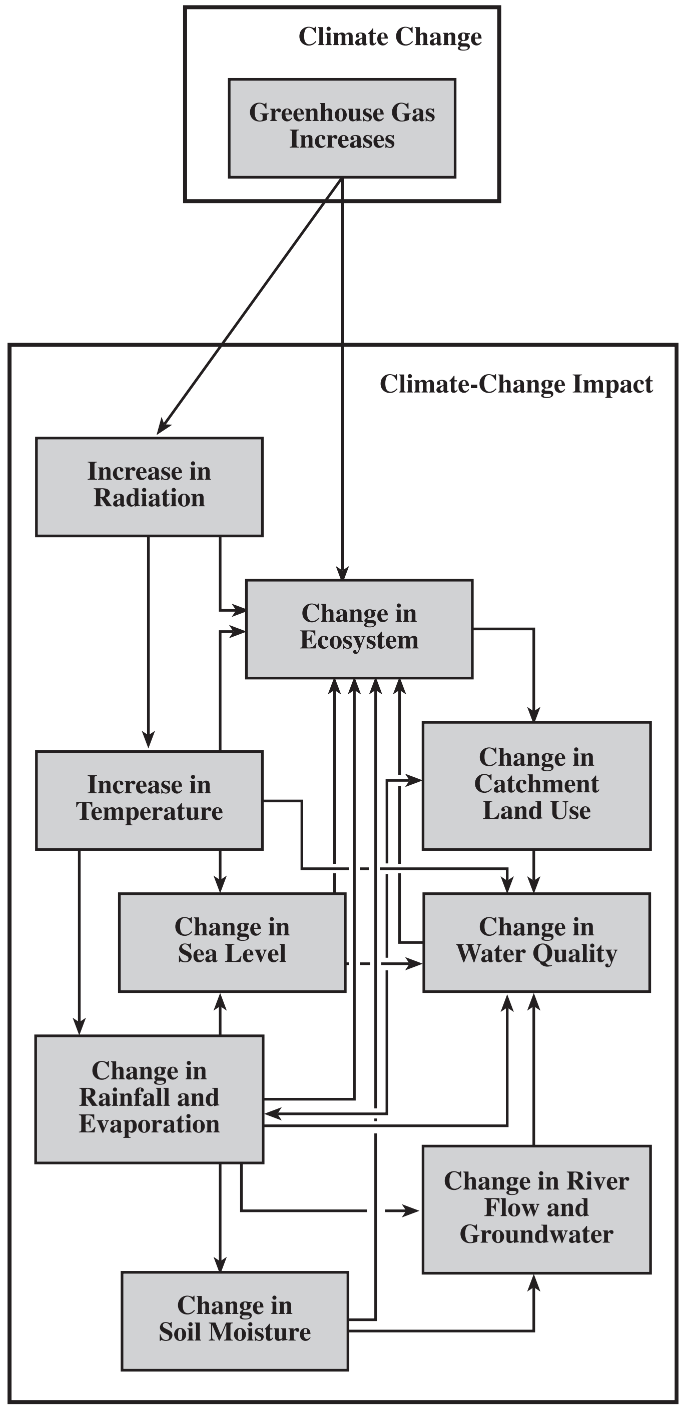

Figure 10-2: Impacts of climate change on the hydrological system (Arnell, 1994).

components of the hydrological system are very clearly linked, and the effects of global warming may be very complex. This complexity is heightened by nonlinear responses and important thresholds in the hydrological system that govern the operation of different types of processes.

The following sections summarize global-warming impacts on various components of the hydrological system. Table 10-1 provides a selection of case studies from the recent literature. Case studies are not available for all regions, but an attempt has been made to list some of the modeling assumptions employed. The results of the studies should be examined in association with the caveats noted in Section 10.2.3 and with the knowledge that hydrological models may not adequately portray the true responses of the modelled processes.

10.3.2. Precipitation

Globally, climate change may result in a wetter world. Present-day climate models project an increase in global mean precipitation of about 3–15% for a temperature increase of 1.5–4.5°C. Although it is likely that precipitation will increase in some areas and decline in others, climate models are not in agreement as to the amount or the regional distribution of precipitation. Projections of regional changes in precipitation are less certain than projections of regional changes in temperature. Higher-latitude regions are expected to experience more precipitation, particularly in the winter. In most cases, this extends to mid-latitudes. Models vary significantly in terms of how the intensity and statistical distribution of rainfall is predicted to shift in the tropics, although little change is expected for the dry subtropics.

10.3.3. Evaporation and Transpiration

Evaporation is a function of the demand for water and the supply of water. It is driven by energy availability, particularly net radiation. An increase in net radiation will increase the demand for evaporation, but this effect will be complicated by changes in the humidity of the air—affecting the ability of the air to accept more water—and by changes in the rate of movement of air across the evaporating surface. In addition, the humidity of air masses is strongly linked to evaporation over land and water bodies, including the oceans. With credible assumptions about increases in radiation and reductions in humidity, a rise of about 2°C could cause an increase in potential evaporation of up to 40% in a humid temperate region (Arnell and Reynard, 1993), but less in a drier environment where changes in humidity are not very important. Higher temperatures will mean that the atmosphere can hold more water—thus enhancing the effects of increased net radiation on evapotranspiration in regions where air humidity currently imposes a constraint on the rate of evaporation (as in humid areas).

The actual evaporation rate often is constrained by moisture availability. A reduction in rainfall or a change in its temporal distribution, and hence in soil moisture, may mean that

Table 10-1: *Summary of recent case studies.*

Region/Country	Investigators	GCMs/Climate Scenarios[1]	Hydrologic Scenarios
Australia			
6 Catchments	Bates *et al*. (1995)	CSIRO 9 (1991)	Increase in magnitude of annual maximum monthly runoff series, with size of increase dependent on hydrological model; increase or decrease in median monthly runoff dependent on location and season.
28 Catchments	Chiew *et al*. (1995)	Hypothetical + BMRC, CCC, CSIRO 9, GFDLH + UKMOH	Annual runoff changes of ±50%; annual soil moisture level changes of -25 to +15%.
China			
Haihe, Huaihe, and Yellow River Basins	Liu *et al*. (1995)	Output from seven GCMs used as input to hydrological models	Decrease in annual runoff of 2–12%.
Finland			
12 Catchments	Vehvilainen and Lohvansuu (1991)	GISS	Increase in mean discharge by 20–50%; considerable increase in mean minumum discharges in winter due to shorter snow-cover period; decrease in mean maximum discharges due to reduced maximum snow water-equivalents; persistent winter snow cover will vanish in southern Finland.
Greece			
Mesochora Catchment	Panagoulia (1992)	GISS	Decreased spring and summer runoff, soil moisture, and mean snow accumulations; increased winter runoff and soil moisture.

Table 10-1 continued.

Region/Country	Investigators	GCMs/Climate Scenarios[1]	Hydrologic Scenarios
Hungary			
Danube Basin	Gauzer (1993)	Hypothetical temperature scenarios	Considerable increase in winter streamflow and decrease in summer applied to September 1991–August 1992 flow; no decrease in spring flood peak, but change in timing.
Drainage Systems	Novaki (1990, 1992a, 1992b)	Hypothetical precipitation and temperature scenarios	1–2°C increase in temperature and 5–20% decrease in annual precipitation may cause 15–30% decrease in drainage discharge at start of spring.
India			
Kolar and Sher Basins	NIH (1994)	Hypothetical scenarios	Sher Basin more sensitive to climate change; impacts large enough in central India to influence storage design and operation.
Japan			
Various	Harasawa (1993)	Not known	Reduced snowfall, hence snowmelt; changed amount and seasonal pattern of water resources; impacts on water quality.
Nepal			
Lantang Kola Catchment	Fukushima *et al*. (1991)	Not known	Increase in river flow of 100% with stable glacier area; +30% if glacier area decreases by 30%.
South Asia			
	Lal (1994)	ECHAM 3–Hamburg	Increase in soil moisture over central India, Bangladesh, and south China in summer; significant decline in soil moisture over central China in winter; increase in runoff over northeastern India, south China, and Indonesia; decline in runoff possible over north China and Thailand.
Switzerland			
Murg Catchment	Bultot *et al*. (1992)	Various sources	Decreased annual deep percolation; increased winter runoff, but little change to annual flow; reduced soil moisture content in summer; shorter spells with snow cover.
Ukraine			
Poles'e River Basin	Nazarov (1992)	Scenarios in Houghton (1991)	Increase in annual runoff of 6%; decrease in evapotranspiration of 2%; decrease in soil moisture storage of 17%.
United Kingdom			
England and Wales Catchments	Arnell (1992)	Hulme and Jones (1989)	Increases in mean annual runoff of 13 to 30% for 10% precipitation increase (15 inches annual rainfall).
United States			
Boston	Kirshen and Fennessey (1993)	GFDL (1988), GISS (1982), OSU (1984–85), UKMO (1986)	Decrease or increase in reservoir-system safe yield, depending on GCM used.
American River, Washington	Lettenmaier (1993)	2–4°C uniform temperature increase	Snow accumulation substantially reduced; high-flow season shifted from spring to winter; peak actual evaporation shifted to spring or early summer due to reduced soil moisture.
Delaware River Basin	McCabe and Wolock (1992)	GFDL, GISS, OSU	Considerably drier conditions than present; future soil moisture decrease partly masked by interannual variability, and amount of decrease varies according to GCM used.
Trinity, Colorado, and Rio Grande Basins	Schmandt and Ward (1993)	Hypothetical scenarios	Difficulty in meeting demand in 2030 under record drought conditions; severe shortages under 2°C increase and 5% decrease in precipitation.
Texas (6 Sites)	Valdés *et al*. (1994)	Various sources	Decrease in mean soil moisture concentration.

[1] Acronyms used in Table 10-1 follow: Bureau of Meteorology Research Center (BMRC), Canadian Climate Center (CCC), Commonwealth Scientific and Industrial Research Organization (CSIRO), Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), Oregon State University (OSU), and United Kingdom Meteorological Office (UKMO). GFDLH + UKMOH refers to high-resolution GFDL and UKMO models.

actual evaporation would decline even if evaporative demand were to increase.

The evaporative loss of water from vegetation, or transpiration, is influenced by vegetative properties such as albedo, surface roughness, root depth, and stomatal characteristics—and all of these may change with climate. The timing of plant growth and the species of vegetation in a catchment also might change. Plant water use also is related to atmospheric CO_2 concentrations. There are two main effects. First, there is experimental evidence that some groups of plants use water more efficiently when CO_2 concentrations are higher, leading to reduced transpiration (Dooge, 1992; Drake, 1992). Kimball *et al*. (1993) found that spring wheat grown at a CO_2 concentration of 550 ppm had an evaporation rate 11% lower than wheat grown at 370 ppm. The modeling studies of Kuchment and Startseva (1991) show that CO_2 enrichment can lead to a decrease in evapotranspiration despite climate warming and that evapotranspiration responses to changes in climate variables and plant factors can differ greatly from those that consider temperature changes alone. Second, many plants grow more when CO_2 concentrations are higher, and the increased leaf area may compensate for the increased leaf water-use efficiency. These experimental effects may not be reproduced in the field—where plant growth is subject to limitations in nutrients and moisture, as well as competitive interactions—and there is some evidence that plants acclimatize to increased CO_2 concentrations (Wolock and Hornberger, 1991; Dooge, 1992; Hatton *et al*., 1992; Koerner, 1995; Chapter A; Chapter 9, *Terrestrial Biotic Responses to Environmental Change and Feedbacks to Climate*, of the Working Group I volume).

10.3.4. Soil Moisture

Depending on rainfall or snowmelt intensities, as well as soil capillary and aquifer hydraulic conductivities, water will infiltrate and percolate into the soil. Soil water storage plays a decisive role in evaporation and evapotranspiration of plants. For a given soil depth and soil type, any change in the seasonal distribution of precipitation or its intensities will change soil water storage, runoff processes, and groundwater recharge. Land use, river flow, and groundwater resources are affected. Improved modeling of the hydrological cycle and of these land-surface processes in GCMs is a critical research issue (Chahine, 1992; Dooge, 1992; Rind *et al*., 1992; Milly and Dunne, 1994).

All climate models show increased soil moisture in high northern latitudes in winter, with some areas of reduction. Most models produce a drier surface in summer in northern midlatitudes and a reduction in summer precipitation over southern Europe. Reductions over North America are less consistent, and there is greater variation between models over northern Europe and northern Asia. When aerosols are included, the patterns of soil-moisture change in the northern winter are similar but weaker, and summer drying over North America and southern Europe is reduced (see Chapter 6, *Climate Models—Projections of Future Climate*, of the Working Group I volume).

10.3.5. Snow-Cover Accumulation and Melt

Mountainous regions are particularly important in a hydrological context. They are source areas of a significant part of the water resources for many continental areas outside the tropics because of orographically induced high precipitation. Water stored as snow during the winter becomes runoff in the spring. Higher global temperatures in winter would result in more precipitation falling as rain rather than as snow, reducing snow-cover duration and causing the ascent of the snow line. These changes would lead to increased winter runoff and decreased spring and summer runoff, resulting in seasonal changes and possible disruptions in supply in regions without reservoir-based water management.

The melting of snow and glaciers is sensitive to changes in air temperature during the melt season, although temperature is only a rough index of melt energy fluxes—which consist of net radiation, sensible heat, and latent heat. Brun *et al*. (1992) used a physically based snow model to investigate the sensitivity of snow cover in the French Alps to increased incoming energy. They found that at an elevation of 1,500 m above sea level, snow cover can be considered "sensitive" during about half of the days of its existence. This means that even a slight increase in air temperature throughout the winter or a few individual warm spells have important consequences in reducing the snow cover. At 3,000 m above sea level, there is about a 6-month period during which the sensitivity to increased energy input is very weak; the sensitive days constitute about 30% of the total snow-covered period, which essentially represents the melting period. It also was shown that the entire area of the French Alps can be considered to react homogeneously to increases in incoming energy at elevations above 2,400 m above sea level, but that below this elevation the southern part of the Alps reacts more sensitively. This effect is related to latitude effects of air temperature and solar radiation.

Not much is known about evaporation in high mountain areas. Although evaporation seems to be of secondary importance in the water balances for these areas, it may play a considerable role in controlling daily variations in melt rates (Lang, 1981). With increasing altitude, vegetation activity decreases, soil (with its capacity to store water) decreases, and the duration of snow cover increases—together contributing to the general decrease of evaporation with altitude. In a warmer climate, evaporation potential is generally expected to increase, which also is expected for high mountainous terrain.

Mountain orography exerts a great influence on the atmospheric circulation at all spatial scales, which affects the horizontal and vertical distribution of precipitation. This is a point of utmost importance. If the directions of atmospheric moisture advection change (as a consequence of a change in the general route and activity of cyclones), the spatial distribution of precipitation in mountain regions could be strongly modified, compared with the general and large-scale results of present GCM simulations. High mountain areas exposed to strong windward and leeward effects will be affected significantly by such changes.

10.3.6. Groundwater Recharge and Storage

Despite the critical importance of groundwater resources in many parts of the world, there have been very few direct studies of the effect of global warming on groundwater recharge. A change in recharge will depend on the balance between an alteration in the recharge season (or the number of recharge events) and the amount of water available for recharge during the season. In northern Europe, it is uncertain whether increased winter rainfall (as simulated by most GCMs) would make up for a shorter recharge season caused by increased temperatures and evaporation in spring and autumn. In semi-arid and arid areas, where groundwater recharge occurs after flood events, a change in the frequency of rainfall occurrence and the magnitude of those events will alter the number of recharge events.

Using a model of water drainage beyond the rooting zone of plants and assuming rainfall changes of ±20% and unchanged vegetation, Peck and Allison (1988) found that recharge may change by -70% to +230% and -60% to +35% for sites near Khorat in northeastern Thailand (summer-rainfall environment) and near Collie in southwestern Australia (winter-rainfall environment), respectively. A 20% decrease in potential evaporation was found to increase recharge by the same amount or more under low-drainage conditions.

Vaccaro (1992) used a coupled stochastic weather generator and a deep-percolation compartment model to study the sensitivity of groundwater recharge in the Ellensburg basin in Washington state to climatic variability in the historical record and projected climate change. He found that the variability in estimated annual recharge under a climate scenario based on average monthly changes in precipitation and temperature for three different GCMs was less than that estimated from the historical record. The median annual recharge for the scenario was 25% lower than that for the historical simulation.

Wilkinson and Cooper (1993) studied the impact of climate change on aquifer storage and river recharge using a simple model of an idealized aquifer-river system. They found that changes in the seasonal distribution of recharge may have a critical effect on rivers supported by baseflow. The delay in the response of slowly responding aquifers to climate change may be large enough to allow adjustments to water-resources planning over an extended period.

Zhang *et al*. (1994) used a groundwater balance model to study the influence of climatic scenarios on groundwater recharge in the area of Jing-Jin-Tang, China. The results show that a temperature increase of 0.6 to 1.3°C and a precipitation change of -2% to +6% will change groundwater recharge within the range of ±5%.

10.3.7. Streamflow

Even in areas where precipitation increases, higher evaporation rates may lead to reduced streamflow. High-latitude regions may experience increased annual runoff due to increased precipitation, but lower latitudes may experience decreased runoff due to the combined effects of increased evaporation and decreased precipitation. Areas where runoff increases may experience more frequent floods and higher lake and river levels.

Regional changes in streamflow are illustrated by a study examining the impact of global warming on the flow of 33 of the world's major rivers. Miller and Russell (1992) found that all rivers in high northern latitudes showed increased flow of an average of 25% in response to increased precipitation. The largest decreases occurred at low latitudes, with a maximum of -43% for the Indus, -31% for the Niger, and -11% for the Nile due to the combined effects of increased evapotranspiration and decreased precipitation. This study used the NASA/GISS GCM and a 3-year model simulation. It found that the computed runoff for a doubled CO_2 climate depends on the model's treatment of precipitation, evaporation, and soil moisture storage (Miller and Russell, 1992). The authors also discuss the great discrepancies between observed and simulated river flow in some cases, due to oversimplified and unrealistic representations of the hydrological cycle in current GCM models.

Streamflow is highly sensitive to climate change. Shiklomanov (1989) presents a contour map of changes in mean annual runoff of rivers in the former Soviet Union (FSU) with a rise in global air temperature at an early stage of warming (0.5°C). The map shows a 10–20% decrease in the central regions of the European FSU but a 7–10% increase in the northern European FSU and western and middle Siberia. Georgiadi (1991) reports the work of N.A. Speranskaya, which for the same air-temperature rise suggests decreases in mean annual runoff of 6–20% for the Volga and 15% for the Don river systems, an increase of 7–10% for the upper reaches of the Yenisei and Ob river system, and an increase of 5–20% for the Amur river system.

The case studies in this chapter provide a clear indication that dry areas are more sensitive than wet areas to climate variations. Low-flow and dry climates will be more affected than high-flow and humid regions. Warming of the atmosphere alone will decrease streamflow far less than warming accompanied by changes in precipitation. In the case studies presented in this chapter, some areas show increasing annual and monthly flow due to increased precipitation, while other regions show decreased flow due to increased evaporation or decreased precipitation or both. High-latitude regions belong to the former category, lower latitudes more to the latter. Depending on specific scenarios, model simulations may produce an increase or a decrease in annual river flow for the same region, as well as changes in the variability of river flow through the year.

All regions with snowmelt flow regimes point out a shift of seasonal high flow from early summer and spring to the winter season. These regions will very probably have more low-flow problems in the summer. Plain regions with snowmelt floods in the melt season will have fewer meltwater floods in the future scenario—because of decreased snow precipitation—and therefore less snow water-equivalent storage.

Conceptual snow and runoff models have been used to simulate discharge from mountain regions under changed climate conditions (e.g., Kuchment *et al*., 1987, 1990; Lettenmaier and Gan, 1990; Bultot *et al*., 1992, 1994; Rango, 1992; Braun *et al*., 1994). The necessary model parameter values have been evaluated under present-day conditions, usually with the assumption that these parameter values do not change under changed climatic conditions. Most studies show a shift of snowmelt runoff to early spring months at the expense of summer months. In heavily glaciated basins, there is a negative feedback between snow cover and discharge: The smaller the seasonal snow cover, the larger the runoff from glaciers due to increased icemelt caused by reduced albedo as soon as the snow cover disappears (see Roethlisberger and Lang, 1987; Chen and Ohmura, 1990). This aspect generally has not been dealt with in sensitivity studies. Another aspect is the increased loss of glacial areas with increasing summer temperatures. The additional contribution of meltwater to streamflow experienced through decades of strong glacial shrinkage would gradually turn into decreasing streamflow rates. All scenario studies presently available are limited in predictive value because they have distributed the positive temperature change more or less evenly over the year, without taking account of the importance of short-time scale (weather) processes. Detailed discussions of the limitations of GCMs to provide scenarios in alpine regions, and the impact of climate change on these regions, are presented in Beniston (1994) and Chapter 5.

10.3.8. Lakes and Surface Storage

Surface storage waters are important parts of freshwater systems. They often are intensively used for multiple purposes—such as navigation, river flood and low-flow control, recreation, water supply, irrigation, and fishing. To allow an optimal adjustment of water levels, most artificial lakes are regulated, as are natural lakes to some degree. Climate-change impacts on the hydrology of upstream river basins will affect regulated lakes mostly in seasonal and annual regimes and average turnover. Flow and temperature changes also may change the internal stratification of lakes, with consequences to aquatic ecosystems. An increase in air temperature and/or windspeed will cause an increase in lake evaporation.

10.4. Extreme Hydrological Events

10.4.1. Floods

Although the potential impact of climate change on the occurrence of flood disasters has been alluded to frequently in popular accounts of global warming, there have been very few studies addressing the issue explicitly. This is largely because it is very difficult to define credible scenarios for changes in flood-producing climatic events (Weijers and Vellinga, 1995; Beran and Arnell, 1995). Some assessments of the potential effects of global warming on flood occurrence can be made, and it is useful to distinguish among rain-generated floods, snowmelt-generated floods, and hybrids.

Global warming can be expected to produce changes in the frequency of intense rainfall in a catchment for two reasons: (1) There may be a change in the paths and intensities of depressions and storms, and (2) there probably will be an increase in convective activity (Gordon *et al*., 1992; Whetton *et al*., 1993). Higher sea-surface temperatures can be expected to increase the intensity of tropical cyclones and to expand the area over which they may develop. The IPCC Working Group I Second Assessment concludes from the analysis of several climate-model experiments that rainfall intensity is likely to increase with increasing greenhouse gas concentrations and that there may be an increasing concentration of rainfall on fewer rain days.

The effects of a change in the frequency of high rainfall will depend not only on the change in rainfall characteristics but also on the characteristics of the catchment. Small catchments with impermeable soils will be very responsive to short-duration intense rainfall; larger catchments, and those with more permeable soils, will be sensitive to longer-duration storm rainfall totals and general catchment wetness.

Changes in the magnitudes of snowmelt and rain-on-snow floods will deserve particular attention in some regions. The magnitudes of snowmelt floods are determined by the volume of snow stored, the rate at which the snow melts, and the amount of rain that falls during the melt period. Many studies have simulated a reduction in snow cover after global warming, but higher precipitation totals still may lead to a greater volume of snow being stored on the catchment. Floods caused by snowmelt may therefore either increase or decrease. A reduction in snow cover also may mean that more rain-generated floods occur during winter, leading to a shift in the seasonal distribution of floods.

A few studies have attempted to quantify changes in flood occurrence. Gellens (1991) used a daily rainfall-runoff model to simulate river flows in three Belgian catchments, assuming an increase in rainfall during winter. He found more frequent floods, with flows remaining above high thresholds for longer periods. The mean annual flood peak increased between 2 and 10% under the scenario used, with the greatest increase in the most-responsive catchment. Bultot *et al*. (1992) used the same model and scenario to estimate possible changes in flood frequency in a small Swiss catchment and found the same results; the mean annual flood increased by 10%.

For the Sacramento-San Joaquin basin in California, Lettenmaier and Gan (1990) found a reduction in snowmelt floods but an increase in the frequency of rain-generated floods, with a consequent increase in the occurrence of a particular discharge being exceeded. Knox (1993) examined a 7,000-year geological record of overbank floods for upper-Mississippi River tributaries in North America. He found that changes in mean annual temperature of about 1–2°C and changes in mean annual precipitation of less than 10–20% can cause large and abrupt adjustments in the magnitudes and frequencies of floods.

Kwadijk and Middelkoop (1994) investigated potential changes in flood risk in the Rhine basin, using both hypothetical change scenarios and scenarios based on GCM simulations, and found large changes in the frequency of given threshold events; an increase in precipitation and a rise in temperature would lead to major increases both in flood frequencies and in the risk of inundation. However, the hydrological simulations were limited to a monthly time-step. At this temporal resolution, the simulation of snow cover is not reliable—especially at low elevations, where the snow cover is built up and disappears again several times, in time scales of days, during one winter.

Liu (1995) simulated increases in the variability of floods over time and in flood frequencies in both northern and southern China. Bates *et al*. (1995) used a stochastic weather generator coupled with two daily rainfall-runoff models to investigate changes in the behavior of annual maximum monthly runoff series for six Australian catchments within a variety of climatic settings. In five cases, the series were noticeably higher for a changed climate than for the present day. The sizes of projected changes were found to depend on the rainfall-runoff model chosen.

There is evidence from climate models and hydrological impact studies that flood frequencies are likely to increase with global warming. The amount of increase is very uncertain and, for a given change in climate, will vary considerably between catchments. In some catchments, floods may become less frequent. There are four main reasons for the large uncertainty: (1) It is very difficult to define credible scenarios, at the catchment scale, for changes in flood-producing precipitation; (2) it is often difficult to model the transformation from rainfall (or snowmelt) to flood in a catchment; (3) available climatic and hydrological records often provide limited information about flood events; and (4) at present, in many cases, it is difficult to differentiate the effects of climatic change from those associated with anthropogenic changes to land use.

10.4.2. Droughts

Drought is a relative term that may refer to a period in which actual moisture supply at a given location cumulatively falls short of climatically average moisture supply; soil moisture is insufficient to meet evapotranspirative demands for the initiation and sustainment of plant growth; below-normal streamflow or above-normal reservoir depletion occurs; or a local or regional economy is adversely affected by dry weather patterns (Rasmusson *et al*., 1993).

A decrease in average total rainfall, an increase in the frequency of dry spells due to a decline in rain-days, and an increase in potential evapotranspiration due to higher temperatures have the potential to increase drought frequency and severity and to extend their effects into less-vulnerable areas. Increases in the frequency and magnitude of large rainfall events may result in reduced drought potential if they result in higher soil moisture levels and groundwater recharge (Whetton *et al*., 1993).

The frequency and severity of droughts has received little attention. Four features of most hydrological impact studies make it difficult to assess the effect of climate change on low-flow frequency: (1) Most climate scenarios do not assume any change in interannual climate variability; (2) the rate of occurrence of extreme events in perturbed climate series is influenced strongly by the relative severity of events in the original series; (3) the length of concurrent climatic and hydrological records can be relatively short; and (4) feedback between catchment vegetal cover and atmospheric moisture has been neglected (Savenije and Hall, 1994). Many studies focus on simple descriptive statistics of daily, monthly, seasonal, or annual soil moisture and flow over the simulation period, including minimum annual discharge (Mimikou and Kouvopoulos, 1991); mean minimum discharge (Vehviläinen and Lohvansuu, 1991); annual minimum daily streamflow (Bultot *et al*., 1992); and flow equalled or exceeded 95% of the time (Arnell and Reynard, 1993; Bultot *et al*., 1992).

A few studies have attempted to quantify changes in low-flow or drought occurrence and their impacts. Gellens (1991) examined the behavior of low-flow episodes in three Belgian catchments, each with more than 80 years of records. The low-flow behaviors of the catchments were found to respond differently to climate change. Whetton *et al*. (1993) examined changes in drought occurrence in terms of seasonal soil water deficits for nine Australian sites. Results indicate that significant drying may be limited to the south of Australia. These researchers qualify their results by noting that possible changes in ENSO events due to global warming were not considered because no current GCM simulates ENSO effects. The observed interannual variability of rainfall in north and east Australia is strongly influenced by ENSO. Several researchers have investigated the impact of climate change on reservoir reliability using stochastic weather generators or resampling methods to generate long-term sequences of synthetic weather data (e.g., Nathan *et al*., 1988; Cole *et al*., 1991; Lettenmaier and Sheer, 1991; Wolock *et al*., 1993). Descriptions of these and other similar studies appear in Chapter 14.

10.5. Physical and Chemical Changes in Freshwater Ecosystems

This section integrates freshwater ecosystems via hydrology and presents potential effects of climate change on their physical/chemical properties and processes.

10.5.1. Integrated Landscapes of Lakes and Streams via Hydrology

Inland aquatic ecosystems such as freshwater wetlands (Chapter 6) and lakes and streams (covered in this chapter) represent distinct elements of the hydrologic continuum from the atmosphere to the sea. Water flows first downwind as weather systems and then downhill toward the sea. Patterns of atmospheric deposition are closely related to regional- or continental-scale atmospheric "flow paths" (Galloway and Likens, 1979). Freshwater ecosystems occupy landscape depressions where subsurface flows emerge or surface flows and direct precipitation are channeled or retained. Ecological conditions along the freshwater continuum are determined by local factors (soils, vegetation, lake basin shape, stream gradient, temperature) and the legacy provided by spatially and temporally antecedent patches on this flow path. The interplay of climate and catchment controls biogeochemical processes that add particulates and solutes to water during transport in the catchment and within the stream or lake. These materials and physical features regulate biota in streams and lakes, and feedbacks from ecological processes modify water quality and physical features of freshwater ecosystems. Water quality, fisheries, and recreational values of lakes and streams are determined by interactions between the chemical and physical characteristics and the biota of freshwater ecosystems.

Stream ecology has acknowledged the close link between terrestrial catchments and aquatic systems since Hynes (1963, 1975). Progressive longitudinal changes in channel morphology and in dominant sources of water and organic matter, together with downgradient flow, produce predictable ecological patterns along the continuum from small streams to large rivers (Vannote *et al*., 1980; Minshall *et al*., 1983). Nutrient and organic-matter input to streams is closely related to terrestrial and wetland processes (Bormann *et al*., 1969; Likens, 1984; McDowell and Likens, 1988; Wetzel, 1990) and to the flow path of water controlling its dissolved load. The chemistry of water entering streams in Alaska, for example, is dependent not only on the types of terrestrial vegetation through which water flows but also their sequential order (Giblin *et al*., 1991). Physical and chemical properties of lakes are linked strongly to terrestrial processes via effects on stream discharge and chemistry. Recent studies of lake districts show the importance of landscape influences on internal lake properties (Swanson *et al*., 1988). In headwater lake districts, biotic diversity and ecological functioning depend upon landscape position; higher drainages receive proportionately more input from direct precipitation and differ markedly from those lower in the landscape that receive larger inputs of water and materials from terrestrial sources (Kratz *et al*., 1991, 1996).

Changes in climate influence water supply and quality directly through altered precipitation and atmospheric deposition and indirectly by the altered nature of landscape elements through which water and transported substances pass. Many of the most profound effects of climate change on lakes and streams will involve changes in terrestrial ecosystems that alter water and material inputs to freshwaters.

10.5.2. Changes in Streamflow and Lake Water Levels

Streamflow, groundwater flow, and lake levels respond to changes in precipitation and evapotranspiration. Under hotter and drier scenarios, lower runoff and greater evaporation would reduce stream baseflows and could result in periodic drying of some perennial headwater streams. Even in regions that experience increased annual precipitation, reduced summer rains or still-larger increases in evapotranspiration would produce lower baseflows and increased intermittency in summer. Warmer and wetter scenarios—particularly at higher latitudes—would increase runoff, with some intermittent streams becoming perennial and with higher flows altering channel geomorphology. Some lakes could become smaller or dry up entirely as evaporation exceeds water inputs; others could increase in size where precipitation increases more than evaporation.

Long-term, irregular water-level fluctuations occur mainly in semi-arid and dry tropical regions with distinct wet and dry seasons and high interannual variability (John, 1986). Water-level changes are most pronounced in lakes with relatively short retention times, in association with seasonal precipitation patterns. Paleohydrology and paleolimnology are particularly important approaches for obtaining information on paleo lake levels related to climate change. Analyses point out that lake levels and lake hydrology are sensitive to changes in climate (Almquist-Jacobson, 1995; Digerfeldt *et al*., 1992; Almendinger, 1993; Webb *et al*., 1944). Lake level response to climatic fluctuations, reconstructed using diatoms for the northern prairie region of the United States, shows such sensitivity (Fritz *et al*., 1993, 1994; Laird *et al*., 1996). Moon Lake

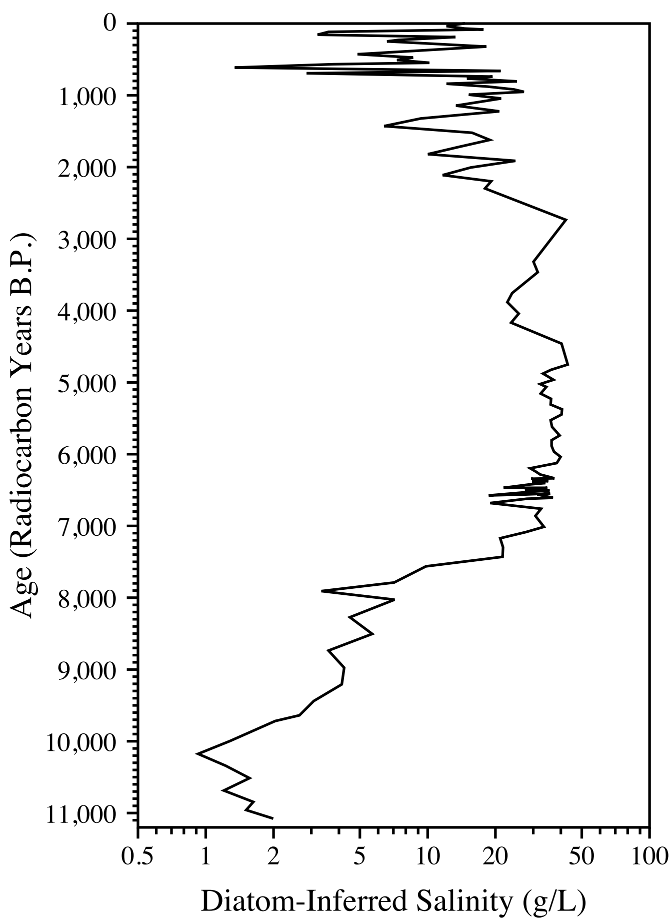

Figure 10-3: Changes in salinity of Moon Lake over the last 11,000 years, inferred from diatom assemblages in sediments (Laird *et al*., 1996).

underwent three major changes in climate: a mid-Holocene period of high salinity indicative of low effective moisture; a transitional period from 4700–2200 before present (BP) with poor diatom preservation; and a late-Holocene period of lower salinity and greater variability, indicating fluctuations in effective moisture (Figure 10-3). Large lakes in the Great Basin of the United States underwent considerable variations in lake levels during the Pleistocene (Benson *et al*., 1990), and similar variations have been inferred for Mono Lake, California (Stine, 1990).

Lakes have individualistic and often rapid responses to climate changes (Figure 10-4). Lake Titicaca experienced a 6.3-m rise in water level from 1943 to 1986. This increase equals 140 mm per year and exceeds by a factor of 40 the change in mean sea level estimated from global warming. Even Lake Michigan, at temperate latitudes, has oscillated over a 1.7-m range from 1960 to 1993. Fluctuations in lakes with large temporal changes in water level are expected to be exacerbated by climate change.

Larger changes in lake water levels are likely at high latitudes where climate warming scenarios are greatest. In the largest Antarctic desert, the McMurdo Dry Valleys, closed-basin lakes fed by glacier meltwater streams, rose as much as 10 m from 1970 to 1990, or almost 480 mm per year (Chinn, 1993). Marsh and Lesack (1996) project with a hydrologic model and a 2 x CO_2 climate that many lakes in the Mackenzie Delta in the Canadian arctic could disappear in several decades owing to decreased precipitation and flood frequency. Some drainage lakes (no inlets but with an outlet) and seepage lakes (no surface inlet or outlet) in the north central United States (Eilers *et al*., 1988a) are responsive to changes in precipitation; during recent droughts in the late 1980s, lake levels declined substantially. Some of these lakes operate as drainage lakes during high water and as seepage lakes during dryer periods.

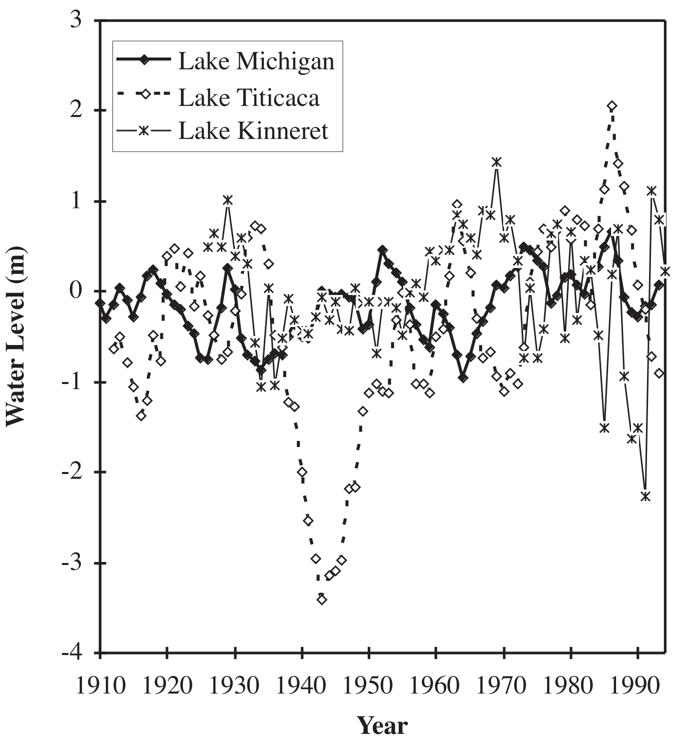

Figure 10-4: Water levels as deviation from the mean for Lakes Kinneret (Middle East), Michigan (North America), and Titicaca (South America) from 1912 to 1993. For Lake Michigan, changes in lake level were calculated as the deviation of the mean annual lake level from the long-term mean lake level (1860–1993) from National Ocean Service, National Oceanic and Atmospheric Administration, USA. For Kinneret and Titicaca, deviation was calculated as the difference between mean annual minimum and maximum water levels and long-term mean [1926–1994 for Kinneret (Serruya, 1978; Gophen and Gal, 1991) and 1912–1993 for Titicaca (Aquize, pers. com.)].

Despite relatively small climatic changes predicted for the tropics, tropical lakes also may be quite sensitive to climate change (see Box 10-1). The level of Lake Victoria (East Africa) rose rapidly in the early 1960s following only a few seasons with above-average rainfall and has remained high since (Sene and Pinston, 1994).

Patterns of water-level change are sensitive to global warming scenarios. For Lake Michigan, 2 x CO_2 scenarios produce a reduced net basin water supply and a lowering of water level of 1 to 2.5 m, depending on the GCM used (Croley, 1990). Assuming that atmospheric CO_2 will double in 33–40 years (see Chapter 6, *Climate Models—Projections of Future Climate*, of the Working Group I volume), this constitutes a decline in water level of 25 to 62 mm/year and exceeds by a factor of about 10 (in the opposite direction) increases in mean sea level estimated from global warming.

10.5.3. Changes in Biogeochemical Fluxes

Physical and biological characteristics of catchments—such as geology, soils and microbes, vegetation, and dominant flow paths of water—control the chemistry of surface water and groundwater. If the water table is close to the surface, flow is routed primarily through organically rich and biologically active upper soil horizons; concentrations of most major ions are lower and concentrations of dissolved organic material higher than if water tables are deep and water moves through lower mineral soil horizons and bedrock before entering lakes or streams. Vegetation and soils, in conjunction with hydrologic flow paths, control the effects of nutrient inputs from atmospheric deposition or fertilizer applications. In agricultural catchments, the effects of fertilizer application on surface-water nutrient concentrations are reduced substantially if water moves through riparian areas where natural vegetation has been preserved (Peterjohn and Correll, 1984). Climate changes that alter hydrologic flow paths or vegetation and soil characteristics will result in changes in groundwater and surface-water chemistry. For streams, these chemical shifts may be episodic or seasonal; for lakes with long residence times, the shifts may be in average chemical characteristics.

Dynamic, process-based water-quality models are needed to

Box 10-1. African Lakes and Climate Change

African Great Lakes are sensitive to climate variation on time scales of decades to millennia (Kendall, 1969; Livingstone, 1975; Haberyan and Hecky, 1987). Lake Victoria (the world's second-largest freshwater lake by area), Lake Tanganyika (the world's second-deepest lake), and Lake Malawi were closed basins for extended periods in the Pleistocene and Holocene (Owen *et al*., 1990). Lakes Malawi and Tanganyika were hundreds of meters below their current levels; Victoria dried out completely. Today these lakes are in delicate hydrologic balance and are nearly closed. Only 6% of water input to Tanganyika leaves at its riverine outflow—which was blocked totally when the lake was explored by Europeans (Bootsma and Hecky, 1993).

Higher temperatures would increase evaporative losses, especially if rainfall also declined. Minor declines in mean annual rainfall (10–20%) for extended periods would lead to the closure of these basins even if temperatures were unchanged (Bootsma and Hecky, 1993). Tropical temperatures are increasing; temperatures in the 1980s were 0.5°C warmer than a century earlier and 0.3°C warmer than from 1951–1980. Concurrently, Lake Victoria's epilimnion was warmer by 0.5°C in the early 1990s than in the 1960s (Hecky *et al*., 1994). Although current climate scenarios project small increases in tropical temperatures, small changes in temperature and water balance can dramatically alter water levels, as well as mixing regimes and productivity.

Recent temperature and rainfall data and GCM simulations indicate increasing aridity in the tropics (Rind, 1995). Increases of 1–2°C in air temperatures could substantially increase the stability of stratification in permanently stratified Tanganyika and Malawi. Their deep waters are continuously warm, but the less than 1°C difference between surface and deep water in warm seasons maintains a density difference that prevents full circulation. Lake Tanganyika's deep water has been characterized as a "relict" hypolimnion that formed under a cooler climate within the past 1,000 years (Hecky *et al*., 1994). Since then, warming has created a barrier to vertical circulation. Additional warming could strengthen this barrier and reduce the mixing of deep, nutrient-rich hypolimnetic water and nutrient-depleted surface layers; that mixing sustains one of the most productive freshwater fisheries in the world (Hecky *et al*., 1981).

estimate effects of climate change because biogeochemical processes controlling water quality are complex. Such models must accurately represent the hydrologic regime—especially the timing and intensity of infiltration (rainfall and snowmelt), as well as the various flow paths through the catchment and changes in vegetation. Examples of coupled hydrologic-water quality models being developed include the Regional HydroEcological Simulation System (Band *et al*., 1996), modifications of Topmodel for transport of dissolved organic material (Hornberger *et al*., 1994), and the Alpine Hydrochemical Model (Wolford and Bales, 1996).

Streams in catchments with low acid-neutralizing capacity periodically may become more acidic. Higher-elevation streams and lakes may receive larger pulses of acidity in the spring if winter snowfall increases or snowmelt occurs over a shorter period—for example, the modeled response with the Alpine Hydrochemical Model for the Emerald Lake catchment in the southern Sierra Nevada region of the United States (Wolford and Bales, 1996). In mountain streams of the southeastern United States, Mulholland *et al*. (1996) project an increase in the frequency or duration of acidic episodes with an expected increase in storm intensity. However, in the northeastern United States, reductions in winter snowpack with climate warming might reduce the intensity and duration of stream acidification in the spring (Moore *et al*., 1995, 1996). At boreal latitudes, soil drying associated with climate warming can lead to oxidation of reduced forms of sulfur in soils and concurrent acidification of streams (Bayley *et al*., 1992b; LaZerte, 1993; Schindler *et al*., 1996; see Box 10-2).

Warmer climates could affect nitrate fluxes through changes in microbial processing rates. Higher temperatures may lead to increased mineralization of organic nitrogen in soil, with increasing amounts available for flushing into lakes and streams. Peak nitrate concentrations in United Kingdom catchments tend to occur following flushing by heavy rainfall after prolonged dry spells; an increase in the duration of dry spells would increase the leachable nitrogen accumulating in soils (Jenkins *et al*., 1993).

For lakes, position in the local groundwater flow system affects their chemical response to shifting hydrologic conditions. Two mechanisms control drought response in northern Wisconsin (Webster *et al*., 1996): Longer residence times and evapoconcentration in lower lakes cause conservative solutes to increase in concentration, whereas lesser inflow of solute-rich groundwater in higher lakes decreases solute concentrations. In prairie lakes and wetlands of north-central United States and Canada, differences in local geomorphology, groundwater flow paths, and vegetation produce somewhat different responses in water chemistry to droughts, with salinity increasing in some and decreasing in others (Evans and Prepas, 1996; LaBaugh *et al*., 1996).

Export of organic matter from terrestrial systems to streams and lakes is expected to change with climate. The amount of wetland drainage strongly influences the concentration of dissolved organic carbon in streams and rivers (Mulholland and Kuenzler, 1979; Eckhardt and Moore, 1990), and changes in

Box 10-2. Climatic Warming Effects: Boreal Lakes and Streams

Boreal soft-water lakes and streams at the Experimental Lakes Area (ELA) in Ontario, Canada, represent numerous ecosystems throughout North America and Eurasia. At ELA, natural variability has been studied for the past 25 years through measurements of climatic, hydrological, physical, chemical, and biological parameters. Analyses of this warmer and drier interval have provided a holistic picture of the potential interactive responses of lakes and streams to climate warming (Schindler *et al*., 1996, and references therein). The almost 2°C of warming and more than 50% decline in runoff are comparable to GCM predictions for a 2 x CO_2 climate. Biological responses in the lakes were linked to changes in biogeochemical processes in the catchments and physical properties of the lakes. Major changes were in:

- *Hydrochemical fluxes*: Export of many constituents decreased in response to decreased streamflow, weathering rates, and decomposition of organic material; drier soils resulted in shorter periods of elevated water tables and saturated soils. Export of dissolved silica and dissolved organic carbon (DOC) decreased more than 50%. Base cations decreased less, suggesting that dry or burned vegetation was less efficient at retaining base cations than vegetation with adequate moisture. Export of acid anions generally decreased, but acid anions increased relative to base cations—causing lower alkalinity and pH in streams. Soil drying apparently enhanced oxidation and the release of sulfate. Nitrogen and phosphorus flux increased somewhat after drought-enhanced fires and major windstorms, but overall export of these nutrients declined.
- *Lake physics, chemistry, and biology*: The lakes generally became warmer and more transparent, and the increased transparency facilitated the deepening of thermoclines (Figure 10-5). The average ice-free period increased by about two weeks. Even though exports from catchments decreased, concentrations of many inorganic constituents increased because residence time in the lakes and evaporative concentration increased. Unlike streams, lakes became more alkaline because lake processes dominated—with longer residence times specifically from the removal of sulfate by microbial reduction and the dissolution of base cations in lake sediments. Slight increases occurred in phytoplankton biomass and species diversity; primary productivity and chlorophyll concentrations did not change. In one lake, suitable habitat for lake trout was reduced and lake trout disappeared.

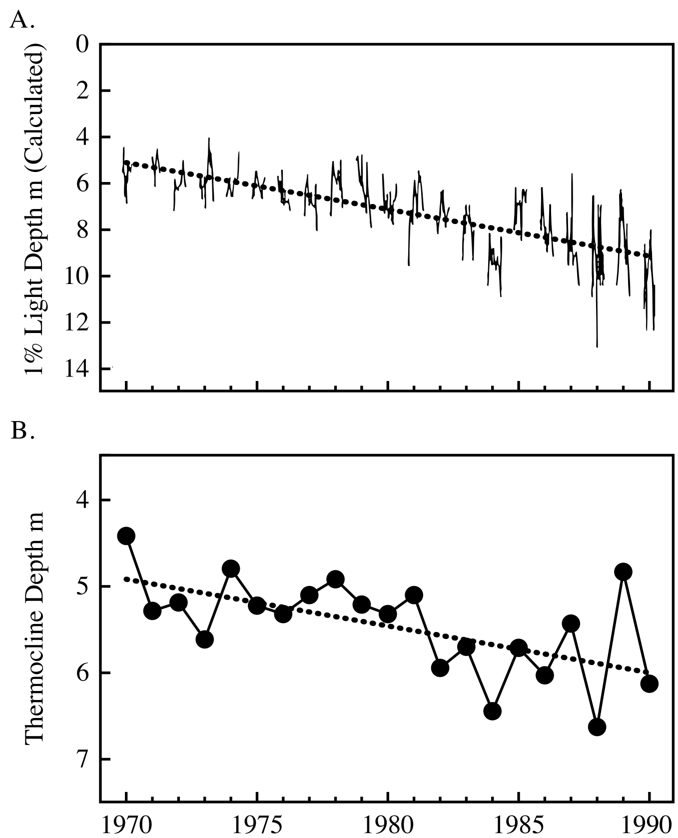

Figure 10-5: (A) Changes in penetration of photosynthetically active radiation (PAR) as the depth of isopleth representing 1% of surface light (equivalent to photic zone depth), from Schindler *et al*. (1996); (B) changes in depth of thermocline.

wetland distribution and connectivity with streams and lakes would alter DOC concentrations. Drought can reduce DOC inputs to streams and lakes on the Canadian Shield (Schindler *et al*., 1996). Changes in the amount and chemical form of organic-matter inputs can occur because vegetation is altered in the catchment overall or in the riparian zone (Band *et al*., 1996). Increasing atmospheric CO_2 or climatic warming may increase the rate of organic-matter inputs to streams because riparian plants produce more foliage, and species composition may change (Bazzaz, 1990)—which in turn would increase production of heterotrophic organisms. This might be countered by drier conditions that would reduce organic-matter inputs from riparian zones. Complexities become most apparent when considering interactions between organic matter and nutrient inputs. Higher atmospheric CO_2 concentrations may increase plant foliage but reduce its nitrogen content (Koerner and Miglietta, 1994); rates of organic-matter decomposition and production in detritus-based food webs actually might decline (Meyer and Pulliam, 1992). Under drier climates, reduced runoff from streams that drain wetlands could reduce inputs of dissolved organic carbon but increase inputs of nitrogen from increased organic-matter oxidation. In a simulation of such changes in a Welsh peatland stream, primary production increased (Freeman *et al*., 1994).

In warmer, drier climates, an increase in wildfires can increase runoff, sediment, and nutrient load (Schindler *et al*., 1980). Wildfires also cause longer-term (5–50 years) reductions in woody debris and material retention in streams (Minshall *et al*., 1989).

Observations over a 20-year period of warmer and dryer conditions at the Experimental Lakes Area (see Schindler *et al*., 1996) illustrate the complex interactions and responses that can be anticipated from climate warming and the value of careful long-term study of aquatic ecosystems to identify critical processes and interactions (Box 10-2).

10.5.4. Changes in Temperature, Dissolved Oxygen and Carbon Dioxide, and Light

Stream water temperature is determined by air temperature, the origin of streamflow (groundwater is often cooler than quick flow in temperate-zone warm seasons), local shading of the stream, and, to a lesser extent, flow volume. Changes in stream temperatures are about 0.9 times as great as changes in air temperature in the UK (Webb, 1992) and the north-central United States (Stefan and Preud'homme, 1993). Simulations from air temperature increases of 1.5° to 4.5°C, using a heat-balance model, produce increases in summer stream temperatures of 2.4° to 4.7°C for Minnesota (Stefan and Sinokrot, 1993). Projected increases in stream temperatures are substantially greater if riparian vegetation is removed, as are stream temperatures where riparian vegetation is experimentally removed (Burton and Likens, 1973). Higher water temperature, along with lower streamflows, could lead to reduced oxygen concentrations in streams receiving organic loading from effluents or in eutrophic streams, where warmer temperatures could stimulate algal blooms.

Thermal regimes in lakes are responsive to climate change because they are controlled by solar radiation, wind velocity, air temperature, humidity, and evaporation, as well as by lake area, depth, and transparency. In north temperate regions, 2 x CO_2 climate scenarios increase summer epilimnion (surface mixed waters) temperatures by 1–7°C, and hypolimnetic (deep cooler waters) temperatures change by -6 to +8°C depending on the size and morphology of the lake (Stefan *et al*., 1993; DeStasio *et al*., 1996; Magnuson *et al*., 1995). Warming increases the duration of warm-season stratification and the sharpness of the metalimnion (the zone of sharp temperature change, >1°C/m, between the epilimnion and hypolimnion). Warming decreases the duration of ice cover or the frequency of winters with winter ice cover. To the south, loss of lake ice cover at some latitudes indicates that lakes that mix twice per year in spring and fall would become monomictic—that is, they would mix through the fall, winter, and spring and stratify longer in the summer. To the north, some lakes that presently are monomictic and mix during summer would stratify in summer and mix twice a year in spring and fall. Some deep lakes that mix twice a year would be less likely to mix completely (McCormick, 1990). Changes in the water level of shallow lakes could change the heat budget or the mixing properties of lakes.

Changes in catchment DOC fluxes would change the mixing regimes of lakes because water clarity and light absorbance are partially functions of DOC concentrations (see Box 10-2). The strong effect of DOC inputs on lake mixing properties appears to be limited primarily to lakes smaller than 500 ha, based on Canadian Shield lakes (Fee *et al*., 1996).

Climate change could cause changes in the amount of oxygen entering lakes and streams through direct atmospheric exchange or through changes in lake and stream metabolism. With a warmer climate, concentrations of dissolved oxygen are expected to be lower because concentrations at saturation are lower and respiration rates are higher at higher water temperatures. Upland streams in the UK tend to be fast flowing and oligotrophic, with high dissolved oxygen owing to rapid reaeration rates (Jenkins *et al*., 1993); lowland river systems tend to be slow flowing, with low turbulence and with dissolved oxygen below saturation. Simulations with the QUASAR dynamic water-quality model suggest that higher temperatures and lower streamflow would result in lower oxygen concentrations in UK rivers. Conditions are exacerbated in lowland rivers, which also tend to have agricultural catchments and often are used as disposal routes for sewage and industrial effluents.

Dissolved oxygen levels in lakes, especially in the deep hypolimnetic waters, are responsive to climate warming scenarios. Simulations with 2 x CO_2 climates for Lake Erie in North America (Blumberg and DiToro, 1990) suggest that losses of 1 mg/L in upper layers and 1–2 mg/L in lower layers can be expected, as can an increase in the area of the lake that is anoxic. This is because at warmer lake temperatures, bacterial activity increases in deep waters and surficial sediment, not from a relocation of the thermocline and smaller hypolimnetic volume. Smaller lakes (Figure 10-6) have similar responses to simulations with a 2 x CO_2 climate (Stefan *et al*., 1993; Stefan and Fang, 1994). In surface waters, dissolved oxygen remains above 7 mg/L and declines by not more than 2 mg/L. In deep hypolimnetic waters, simulated concentrations are as much as 8 mg/L lower in midsummer and never less than 2 mg/L lower. Depletion would occur up to 2 months longer than under baseline conditions owing to longer periods of stratification. Declines in dissolved oxygen are projected to occur in productive (eutrophic) and nonproductive (oligotrophic) lakes but to be more rapid and of longer duration in productive lakes. Simulated declines in dissolved oxygen are more apparent in spring and fall because stratification would be extended into these seasons. Changes in water levels would interact with the mixing properties of shallow lakes and thus their oxygen dynamics.

Dissolved CO_2 concentrations are supersaturated with respect to atmospheric concentrations in most lakes and streams (Kling

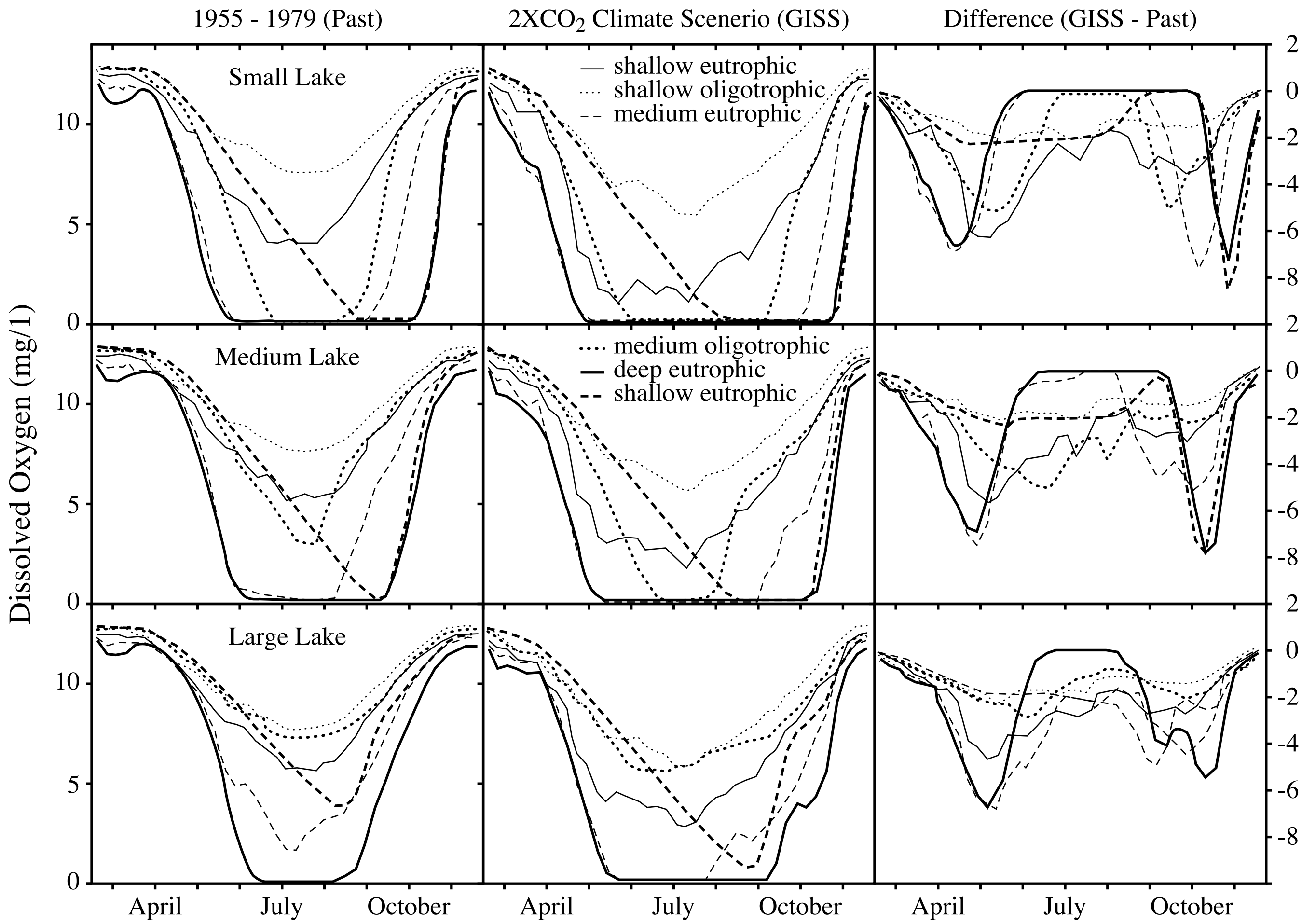

Figure 10-6: Simulated deep-water (hypolimnetic) dissolved oxygen levels in 18 Minnesota lakes (Stefan *et al*., 1993). Past conditions are on the left, projected 2 x CO_2 climate scenario in the middle, and the difference between future and past climate conditions on the right. Small lakes are on top, medium lakes in the middle, and large lakes on the bottom.

et al., 1991; Cole *et al*., 1994)—a result of high CO_2 concentrations in groundwaters and high rates of respiration in many freshwaters. Direct effects of increasing atmospheric CO_2 will be significant only in streams and lakes with low alkalinity and relatively high primary productivity; dissolved CO_2 and HCO_3 concentrations are depleted during daylight, causing increases in pH. In such systems, an increase in atmospheric CO_2 will increase carbon flux from the atmosphere to the water body.

Changes in cloud cover and shading could change light profiles in lakes and streams and affect primary productivity. Light is a major control on photosynthesis in freshwater ecosystems. Reduction in riparian vegetation under drier climates would decrease shading, thus increasing light availability and primary productivity in headwater streams. DOC in freshwaters responds to climate change and alters light availability (see Section 10.5.3 and Box 10-2). High light intensity also can inhibit photosynthesis at the surface, and UV radiation inhibits both algae and invertebrates. Interaction between DOC and UV attenuation is particularly important, given that increased UV radiation is associated with the depletion of ozone. In North American lakes, even small decreases in DOC could significantly enhance the penetration of biologically harmful UV-B radiation into the water column (Scully and Lean, 1994; Williamson *et al*., 1995).

10.5.5. Erosion, Sedimentation, and River Channel Stability

Changes in vegetation, rainfall, and hydrological regimes affect erosion on hillslopes and in river channels, sediment transport and sedimentation, and river channel stability (Schumm, 1977). Separating the effects of climate fluctuations from changes in land use is difficult because land use also affects hillslope erosion and sediment loads in streams and hence the river channel. Three other general points are apparent from published studies: (1) Much geomorphological activity is episodic, occurring during extreme events; (2) there may be critical thresholds in the geomorphological system, beyond which change is more dramatic; and (3) the effects of climate change work through the geomorphological system over many decades.

Soil and hillslope erosion are sensitive to land-use practices and changes in catchment vegetation. In simulations with no change in land use, increased winter rainfall results in greater erosion from arable lowlands in the UK but lower losses from arable fields in uplands because the warmer climate includes longer growing seasons and hence greater ground cover (Boardman *et al*., 1990). Hillslope erosion only occurs once rainfall exceeds a critical threshold in an upland UK catchment (Harvey, 1991). If rainfall frequency and/or intensity were to increase significantly and more erosion were to follow, increased river flows would influence channel erosion, with erosion potential increasing for higher flows. Not all sediment generated on hillslopes reaches the river channel, but increased hillslope and channel erosion should increase sediment loads. Sediment loads in the Yellow River (China) increase in simulations of a conceptual hydrologic and sediment model because high intensity rainfalls were more frequent, even though total runoff decreased in the scenarios (Bao, 1994).

Historical analogs provide useful information about possible changes in sediment loads. Sediment loads on the River Garonne (France) during a wet period in the 1840s were four to five times higher than in drier periods (Probst, 1989). River sediment loads in northern regions will be affected not only by flow regime changes but also by temperature rise. If warming raises temperatures above freezing for longer periods, snow and icemelt and permafrost degradation would increase, releasing more sediment into rivers (Woo and McCaan, 1994). Changes in flow regime and sediment loads would change river channel stability; specifics depend not only on changes in inputs but also on the channel's proximity to a change in threshold. A channel at the boundary between braided and meandering would be more sensitive to change than one with a clearly defined, meandering channel. An upland channel might be most sensitive to changes in the supply of sediments from adjacent hillslopes, whereas a lowland channel would be more sensitive to changes in sediment loads from upstream.

Extreme events are most important in triggering channel change (Newson and Lewin, 1991). Given an increase in the frequency of extreme events (Section 10.4), the location of channel instability and sites of erosion and sedimentation should change, although this will depend greatly on local channel characteristics. Changes in channel geomorphology should be greater in unconstrained alluvial channels, owing to their more dynamic geomorphology, than in constrained channels on or near bedrock. However, as noted by Newsom and Lewin (1991), "The interactions between river channel change, sediment transport, climatic and hydrological fluctuations, and human activities are so complex that a simplistic response model relating morphological response to alternative climate-change scenarios is just not practical at present."

10.6. Lake and Stream Biology

This section considers the potential effects of thermal and hydrologic changes on biological rates, life histories, and reproduction, and resulting changes in geographic distribution and biodiversity, as well as possible adaptations to climate change.

Inland waters are perhaps most sensitive to landscape-level effects of climate change and as such serve somewhat as "canaries" for effects on landscapes. Effects are difficult to dissect into their components because lakes and streams aggregate many other influences of human activity. Lakes and streams, as well as wetlands (see Chapter 6), integrate many human and natural events occurring on the landscape. Streams, in a sense, are the arteries of the continents; lakes and wetlands are the integrative sensors of changes in climate, pollution, and land use (Degens *et al*., 1991). The effects of climate change on terrestrial systems, such as vegetation (see Chapter 1) and land use, are transmitted to and accumulate in freshwater ecosystems. Ecological responses of freshwater to climate change will be exacerbated by other anthropogenic changes.

Climate scenarios used in many of the references cited in this section (and in Section 10.5) differ from the most recent IPCC scenarios. Analyses of climatic warming effects from earlier scenarios may overestimate effects, compared with new analyses with more recent scenarios. Previous IPCC 2 x CO_2 scenarios suggested globally averaged mean annual temperature increases of 1.5° to 4.5°C (IPCC, 1992)—about twice the values from current IPCC scenarios with ramped models and the effect of atmospheric aerosols. Nonetheless, the climate warming effects described in this section are reasonable in direction, if not in magnitude. Current scenarios also suggest that warming will be greater in fall/winter and at night during summer than at other times. Regional differences in future climatic change will be important, and GCM-based global scenarios still do not provide adequate regional scenarios. Regional warming may be considerably less than or greater than globally averaged warming.

10.6.1. Thermal Effects on Biota

Extreme water temperatures can kill organisms. More moderate water temperature variations control physiological rates and behavioral performances, and influence habitat preference (e.g., for fish: Fry, 1947, 1971). Given that species have varying tolerance ranges for temperature, shifts in temperature can produce changes in species composition that can affect the overall productivity of individual freshwater ecosystems and their utility to humans.

Direct effects of climatic warming on the productivity, life history, and reproduction of organisms in streams and lakes will result primarily from increases in average water temperatures and growing season, increases in winter water temperatures and a shorter winter period of cold water or freezing, and increases in maximum summer water temperatures. Indirect effects of warming on productivity and life history include changes in hydrology, especially of extreme events (Section 10.6.2), and in vertical mixing (Section 10.5.4). In streams, ecological effects should be strongest in humid regions where streamflows are less variable and biological interactions control organism abundance (Poff and Ward, 1990). Warming effects should be strong in small, mid-latitude streams where large groundwater discharges currently maintain relatively low maximum water temperatures in summer, as well as in mid-latitude and high latitude streams that experience large increases in annual degree days. Direct thermal effects on lake organisms should be greatest at higher latitudes where the largest changes in temperature are expected.

10.6.1.1. Freshwater Invertebrates

Production rates of plankton and benthic invertebrates increase logorithmically with temperature, with rates increasing generally by a factor of 2–4 with each 10°C increase in water temperature, up to about 30°C or more for many organisms (Regier *et al*., 1990, and citations therein). Macroinvertebrate production rates increased by 3 to 30% per 1°C rise in mean annual water temperature in a comparison of 1,000 stream studies at mid- to high latitudes (Benke, 1993); annual macroinvertebrate production increased and production-to-biomass ratio increased by 3 to 25%.

Regier *et al*. (1990) posit that increases in primary production, zooplankton biomass, and fish yields with temperature indicate that the thermal effects of warming will superficially resemble eutrophication (increasing production from increased nutrients). The effects of these temperature-dependent changes would be least in the tropics, moderate at mid-latitudes, and pronounced in high latitudes. Such increases assume that as temperatures warm, warmer-water assemblages replace the cooler-water ones because in most cases individual species do not continue to increase over the entire temperature range.

Ecosystem production-to-respiration (P:R) ratios decline with warming because respiration increases more rapidly with temperature than photosynthesis does. Even though the photosynthetic rates of many algae increase with temperature—at least up to about 25° to 30°C (Davison, 1991)—ecosystem primary production may increase little because nutrient concentrations and light availability often limit algal production, and these factors also change with climate change. Respiration rates increase with temperature at both the organism and ecosystem levels. At average levels of light and biomass, ecosystem P:R ratio in Arizona declines from 3.0 at 19°C to 1.6 at 30°C (Busch and Fisher, 1981). In Ontario, Canada, the P:R ratio of stream communities on stone surfaces declines from 4 at 4°C to 0.5 at 28°C (Rempel and Carter, 1986). A drop in P:R ratio tends to reduce the average mass of benthic organic matter and/or the export of organic matter downstream (Carpenter *et al*., 1992). Higher rates of microbial respiration with higher temperatures suggest that food resources for invertebrates feeding on seasonally available detritus from terrestrial vegetation might increase in the short term following its input to streams. However, higher microbial respiration rates will increase organic-matter decomposition rates and may shorten the period over which detritus is available to invertebrates (Rempel and Carter, 1986).

Temperature has strong influences on virtually all physiological and life-history parameters (Table 10-2). That is the reason for increases in secondary production rates with temperature. These direct effects can be used with zooplankton as indicators of biotic vitality in systems undergoing changes in climate. At stressful temperatures, survival and reproduction decline while mortality and development times increase (Roff, 1970; Herzig, 1983; Orcutt and Porter, 1983; Cowgill *et al*., 1985; Jamieson and Burns, 1988).

Table 10-2: *Response of physiological characteristics and processes of zooplankton and benthic invertebrates to increasing water temperature, based on studies for which temperature remains well below tolerance limits.*

Process	**Effect of Increasing Temperature**
Life-Stage Development	Faster
Reproduction Rate	Greater
Ingestion Rate	Greater
Growth Rate	Greater
Respiration Rate	Greater
Mortality Rate	Lower
Generation Times	Shorter
Generations per Year	More
Average Body Size	Smaller
Production:Biomass Ratios	Greater

Sources: Lei and Armitage, 1980; Vidal, 1980; Ward and Stanford, 1983; Woodward and White, 1983; Sweeney, 1984; Sweeny *et al*., 1986; Rempel and Carter, 1987; Short *et al*., 1987; Jamieson and Burns, 1988; Maier, 1989; McLaren *et al*., 1989; Abdullahi, 1990; Moore and Folt, 1993; Moore *et al*., 1995a; Hogg *et al*., 1995.

Communities in mid-latitude streams dominated by groundwater springs and seepages are particularly susceptible to climatic warming because summer water temperatures are low in these streams and because increases in groundwater temperatures will be approximately equal to increases in average annual air temperature for the region. Thermal optima for many cold-water taxa from the mid- and high latitudes is less than 20°C; summer temperatures may exceed thermal tolerances and reduce production. The growth rate of the stonefly (*Leuctra nigra*) in the UK increases with temperature in experiments up to about 20°C, but survival is reduced by 67% and egg production by 90% at temperatures between 12 and 16°C (Elliott, 1987). In Pennsylvania, experimental increases in stream temperature during autumn—from ambient, near 10°C, to about 16°C—are lethal to 99% of stonefly (*Soyedina carolinensis*) larvae (Sweeney and Vannote, 1986).

Changes in the temporal pattern of warming may have significant and surprising effects because temperature is a cue that stimulates both the production and the release from dormancy of zooplankton over-wintering stages (Korpelainen, 1986; Stirling and McQueen, 1986; Sullivan and McManus, 1986; Marcus, 1987; Hairston *et al*., 1990; Hairston, 1996; Chen and Folt, 1996). Warming events in autumn could alter the timing or occurrence of resting stages, thus potentially causing the loss of an entire cohort or population and the reduction of eggs in the "seed bank." Resting eggs of the copepod (*Epischura lacustris*) are stimulated to hatch prematurely in autumn by raising temperatures above 15°C (Chen and Folt, 1996).

Invertebrates that can reproduce asexually may be buffered from local extinction at high temperature because they have populations comprising clones with different thermal tolerances. Electrophoretically distinguishable winter and summer clones of *Daphnia magna* from a single pond exhibit large differences in responses to temperatures of 25 and 30°C (Carvalhoe, 1987; LaBerge and Hann, 1990). Winter clones die, whereas summer clones survive and reproduce. This seasonal phenotypic variation in thermal response may increase the ability of these species to adapt. Other species are more likely to go extinct. Glacial relicts (some cold-water species) often lack resting stages and have poor dispersal capabilities. If excessive warming eliminated an entire cohort one year, resting stages would not be available in the sediments to reestablish the population the next year—and local extinction would result. Local extinctions are more likely when warm summer temperatures and anoxia erode the hypolimnetic refuge required by particular species (Dadswell, 1974; Stemberger, 1996).

More-persistent thermal stratification of lakes with warming (Schindler, 1990; DeStasio *et al*., 1996) could reduce secondary productivity. Greater anoxia in the hypolimnion (Section 10.5.4) may eliminate a refuge from predation or from thermal stress. Warmer epilimnetic temperatures could decrease the nutritional quality of edible phytoplankton (Soeder and Stengel, 1974; Ahlgren *et al*., 1990; Moore *et al*., 1995, 1996) or shift the species composition of the phytoplankton community toward less-preferable cyanobacteria and green algae (George and Harris, 1985; Tilman *et al*., 1986; Moore *et al*., 1995a).

Temperature increases can reduce the availability of more-nutritious foods for stream invertebrates as well. Water temperatures exceeding 20–25°C reduce diatom taxa (more nutritious) and increase green algae and cyanobacteria (less nutritious) (Patrick, 1969; Lamberti and Resh, 1983).

10.6.1.2. Fish

Body growth and behavioral performances such as swimming ability and foraging success (Bergman, 1987) are controlled by temperature, as are the hatching success of eggs and survival of larvae (Edsall, 1970; Colby and Nepsy, 1981); all are maximum at some intermediate optimum temperature. In North America, freshwater fish have been grouped into three broad thermal groups—called cold-water, cool-water, and warm-water guilds—based on temperature differences in these optima (Hokanson, 1977; Magnuson *et al*., 1979). As temperatures warm, the performance of each species increases or decreases depending on which side of the optima the temperature began; if dispersal is possible in a heterothermal habitat, each species will have a greater tendency to move into or out of the habitat.

Fish in all three thermal guilds grow faster in 2 x CO_2 climate/lake thermal structure/fish growth simulations for the Laurentian Great Lakes in North America (Hill and Magnuson, 1990), given the assumptions that increased food is available to meet higher metabolic rates and that cooler water refuges are available. For Lake Erie, cold water with sufficient oxygen would not likely be available in the hypolimnion after a warming of this extent (Section 10.5.4), so the assumption of refuges is not always reasonable; for Lakes Michigan and Superior, the assumption is reasonable. (Shallow, unstratified lakes and larger rivers would not be expected to have thermal refuges.) Increased prey appears likely with warming of this extent based on correlation models with inter-lake comparisons of primary production, zooplankton biomass, and fishery yields (Regier *et al*., 1990).

Population simulations for smallmouth bass (*Micropterus dolomieui*) under a 2 x CO_2 climate in the Laurentian Great Lakes (Shuter in Magnuson, 1989a) included thermal effects on reproduction, hatching success, and growth at all life stages. Simulations were made for warmer (Erie), intermediate (Huron), and colder (Superior) lakes. Warming in the models produced greater young-of-year survival in the intermediate and cold lakes but no change in the warm lake; in all lakes, warming produced an earlier age of maturation, greater young-of-year growth, a longer growing season for adults, greater year-class strengths, and larger fishable populations. Similar results would be expected for sea lamprey (*Petromyzon marinus*) in the Laurentian Great Lakes based on the effects of temperature on hatching success and growth (Holmes, 1990)—except that sea lamprey are a problem there, and considerable funds are spent for lamprey control.

Warmer winter temperatures would increase the winter survival of warmer-water fish and decrease the reproduction of fish that require a cold period for normal gonadal development. Because climate scenarios suggest that warming will be greater in winter than in summer, such influences may be significant for populations at the high- or low-latitudinal edges of their ranges. Winter survival would be enhanced for young-of-year white perch (*Morone americana*) at the northern edge of their range in the Laurentian Great Lakes (Johnson and Evans, 1990). Increases in mean annual temperature from logging activities in a British Columbia (Canada) stream also result in earlier emergence of salmon fry, and a lengthened growing season—and, as a result, increased over-winter survival rates (Holtby, 1988). Warmer winter temperatures are not beneficial for all fish because low winter temperatures for sufficient periods are required for normal gonadal maturation in some species (Jones *et al*., 1972). For yellow perch—a cool-water fish—the highest percentages of viable eggs produced were 93% after over-wintering at 4°C, 65% at 6°C, and 31% at 8°C.

10.6.1.3. Contaminant Accumulation

Warming of lakes could increase the occurrence of methyl mercury in lakes and the accumulation of mercury in fish. In lake ecosystems, methylation is positively and demethylation negatively related to water temperature; the ratio of methylation to demethylation increases with temperature (Bodaly *et al*., 1993). In six lakes, 70–80% of the variation in size-adjusted mercury concentrations in fish are associated with temperature:

in cisco (*Coregonus artedi*), northern pike (*Esox lucius*), walleye (*Stizostedion vitreum*), and yellow perch, but not for two bottom-feeding fishes, the white sucker (*Catostomus commersoni*), and lake whitefish (*Coregonus clupeaformis*). Mercury concentrations are not associated with other physical or chemical properties of the lakes.

Heavy metals and pesticide accumulation are greater at higher water temperatures (Reinert *et al*., 1974). In-depth treatment of these processes may be found in Wood and McDonald (1996).

Indirect effects of climatic warming on contaminant accumulation in freshwater plankton are likely to occur as well. Predicted water-chemistry changes, such as a decrease in DOC concentrations, may result in a decrease in chemical binding capacity, as hypothesized by Schindler (1996)—thus causing biotic effects of toxins to increase (Connell and Miller, 1984; Moore *et al*., 1995, 1996).

10.6.1.4. Ice and Snowmelt Effects

Ice cover in lakes and streams is expected to decrease with climatic warming (see Chapter 7). Reduced durations of ice cover are expected under scenarios with 2 x CO_2 climates; at the lowest latitudes where ice now occurs seasonally, ice is not expected to form at all in many winters (DeStasio *et al*., 1996). Observed ice durations decreased markedly during a 20-year period of warming in central North America (Schindler *et al*., 1990). In the Antarctic Dry Valley, ice cover has thinned for some of these permanently ice-covered lakes. Lake Hoare thinned by 20 cm/yr over a 10-year period beginning in 1977; ice cover is now 3.5 m thick (Wharton *et al*., 1992). Because light attenuation by the ice is a major limiting factor, these climate-related changes are expected to cause shifts in the biota of lakes with substantial periods of ice cover (Doran *et al*., 1994).

In the Laurentian Great Lakes, loss of winter ice cover results in year-class failure of lake whitefish, because the eggs incubate over the winter and increased turbulence and winter mixing reduce their survival (Brown and Taylor, 1993). On Grand Traverse Bay, Lake Michigan, the number of winters without ice cover has increased in recent years (Assel and Robertson, 1995). If this trend continues—as is expected with greenhouse warming—the lake whitefish are expected to decline in abundance.

In shallow lakes and the backwaters of large rivers, a decrease in ice-cover duration and especially the absence of ice cover would reduce the winter anoxia common at mid- to high latitudes. This could be countered somewhat by lower water levels, which reduce water volumes under the ice and increase the likelihood of winter kill. Winter kill of fish, owing to loss of oxygen under the ice, is a common occurrence in North America and northern Europe; this severe event greatly influences the fish assemblage structure (Tonn, 1990). Small, shallow lakes in midwestern North America that are anoxic in winter and presently have assemblages dominated by the central mud minnow (*Umbra limi*) would be expected to change to ones dominated by northern pike and largemouth bass (Tonn *et al*., 1990) without ice cover and winter anoxia. In northern Europe, assemblages presently dominated by crucian carp (*Carassius carassius*) would be expected to change to ones dominated by European perch (*Perca fluviatilis*), roach (*Rutilus rutilus*), and other species.

10.6.2. Hydrological Effects on Biota

10.6.2.1. Streams

The largest effects of climate-induced changes in hydrology on productivity in streams and rivers will result from reduction in streamflows predicted for mid-latitudes, changes in the amount and form of winter precipitation and the timing of snowmelt at high elevations, and increases in the magnitude or frequency of extreme events (e.g., floods, droughts).

Reduced streamflows produced by lower precipitation and/or increased evapotranspiration would increase the probability of intermittent flow in smaller streams. Drying of streambeds for extended periods reduces ecosystem productivity because the aquatic habitat is restricted, water quality is reduced (e.g., expanded hypoxia), and intense competition and predation reduce total biomass (Fisher and Grimm, 1991; Stanley and Fisher, 1992). Intermittent streams in Australia and the southwestern United States have invertebrate communities dominated by organisms with resistant life stages and short life cycles (Boulton and Lake, 1992; Gray, 1981). Recovery of benthic invertebrates with the resumption of flow can be slow. More than 4 months were required for recovery of macroinvertebrate biomass following two 12-hour periods of streambed drying in the Colorado River caused by dam operations upstream (Blinn *et al*., 1995). Effects of drought also can be delayed. Effects of reduced recruitment during a drought in an Australian stream were not observed until the following year (Boulton and Lake, 1992).

For perennial runoff streams (Poff and Ward, 1989), the potential for intermittent flow may be particularly great in relatively humid climates that have low baseflows owing to low groundwater discharges; nearly one-half of such streams in the eastern and southeastern United States may become intermittent with only a 10% decline in annual runoff (Poff, 1992). A 14% decline in average annual precipitation for Alabama is projected to result in declines of 50–60% in minimum 7-day stream flows (Ward *et al*., 1992)—greatly increasing the possibility that perennial streams will become intermittent, even in this relatively humid region, because groundwater storage is limited.

Reduction in streamflow is likely to reduce the productivity of large flood-plain rivers and low-gradient streams dependent on periodic flooding. Inundation of flood plains provides expanded food-rich habitat and sources of organisms and organic matter for river ecosystems (Welcomme, 1979; Junk *et al*., 1989; Meyer, 1990). Fish yields are 1.5 to 4 times greater in river-flood plain systems than in equivalent systems without flood-plain inundation (Bayley, 1995). Inputs of organic carbon from flood-plain wetlands account for about 80% of the metabolism in the main channel of a low-gradient stream in Georgia (Meyer and Edwards, 1990). Because organisms in flood-plain rivers and streams are adapted to regular flooding cycles, reduction in flood frequency should have greater effects than increases in flooding. A record flood had little effect on Mississippi River biota, but the absence of a flood during a drought year caused substantial short- and

Box 10-3. Flood and Drought in Aridland Streams

In aridland streams, biomass and productivity are limited severely by both flood scouring and stream drying (Grimm and Fisher, 1992; Grimm, 1993). Small changes in precipitation may produce large increases in flow variability because runoff response to precipitation is nonlinear (Dahm and Molles, 1992). Longer periods of drought and more-intense storms may produce severe streambank and channel erosion because aridland riparian vegetation is sensitive to the availability of water, and unvegetated soils are highly erodible (Grimm and Fisher, 1992).

Changes in the timing of flood and drought may be more important than changes in the annual averages. In the Sonoran Desert of Arizona, stream communities may be shaped by flash floods and subsequent colonization dynamics; biotic interactions, such as competition for a limiting resource; or morphometric and state changes associated with drought—shrinking ecosystem boundaries and eventual loss of surface water (Figure 10-7). These controlling processes are important because they shape community structure, instantaneous and annual primary and secondary production, and nutrient retention.

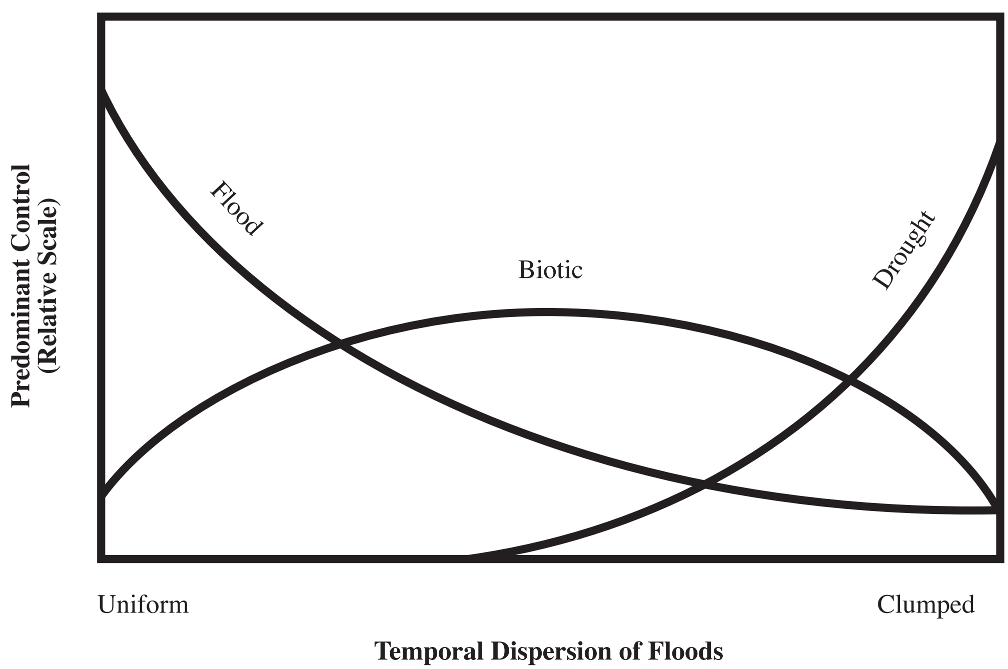

Figure 10-7: Changes in relative importance of major controlling factors in hypothetical years in which annual runoff and storm number are constant but the distribution of floods in time varies.

The contribution of each controlling process to the system's state depends on the temporal pattern of flooding rather than on the total annual discharge. In years with floods evenly distributed in time, drought effects are rare and biotic interactions are moderate. When between-flood periods are long, biotic interactions become more important and drought conditions characterize a substantial proportion of the year (Fisher and Grimm, 1991). In Sycamore Creek, annual runoff in 1970 was equivalent to 1988 but occurred as two flash floods compared to eight in 1988. Consequently, drought dynamics influenced the ecosystem during 76% of 1970 but only 29% of 1988; benthos colonization, succession, and rapid growth and reproduction were prevalent during 55% of 1988 but only 16% of 1970 (Grimm, 1993).

Changes in long-term processes also are important. Catchment-derived fluxes of nitrogen to desert streams are higher in floods that occur after several years of low precipitation (Grimm, 1992), presumably owing to accumulation of nitrate in soils during droughts. Century-scale arroyo-cutting episodes alter drainage patterns, drain wetlands, and shape stream channels (Hastings and Turner, 1965). Small changes in atmospheric circulation patterns exert large effects on the occurrence, timing, and magnitude of convective storms on the Sonoran Desert and thus the flow variability of its streams and rivers.

long-term changes in plant and invertebrate communities (Sparks *et al*., 1990).
Increases in flow variability should produce larger effects than changes in mean flow. Large floods scour the beds of small streams and rivers, flushing organisms and detritus downstream and depressing biomass and productivity for some time. New Zealand streams with more-frequent high flows had lower algal biomass and presumably lower primary production than those with more stable hydrographs (Biggs and Close, 1989).

Streams in arid regions such as the Sonoran Desert of Arizona are particularly susceptible to climate-induced changes in flow variability (see Box 10-3).

10.6.2.2. Lakes

Changes in lake water levels (Section 10.5.2; Figure 10-4) have large effects on nearshore biotic assemblages. In Lake Titicaca, South America, submerged macrophytes experience significant mortality when water levels change more rapidly than they can adapt (see Dejoux and Iltis, 1992). In Lake Kinneret in the Middle East, changes in inshore ecosystems occur with rapid water-level fluctuations, even though upper and lower water levels are regulated; the lake is a major reservoir of Israel's freshwater supply. A 4-m water-level decline in Kinneret reduces the stony belt around the lake by 30–94% (Gafny *et al*., 1992), and the littoral slope changes from steep to slight (Gasith and Gafny, 1990). During low lake levels, wave action affects more areas of soft sediment than at high lake levels, resulting in short-term effects on water quality (Gafny and Gasith, 1989, 1993). Emergent vegetation develops in areas with gentle slope (Gasith and Gafny, 1990). The community of fish breeding in the littoral zone switches from dominance by fish that spawn on stones to those that spawn on sand (Gafny *et al*., 1992). This may affect year-class strength of the primary planktivorous fish and eventually the entire food web. A warmer and drier climate in the Middle East would exacerbate such changes in inshore aquatic communities.

With declining water levels, lakes might in the short term become more separated from their bordering wetlands. A number of lake fish use these wetlands for spawning and nursery areas (Brazner and Magnuson, 1994). Northern pike, which spawn in flooded sedge meadows in early spring and whose young remain for about 20 days after hatching (Becker, 1983), would be especially damaged by low spring water levels.

Connectivity among lakes would be decreased by the cessation of flow in connecting streams in some lake districts, which could influence community structure and rates of extinction and invasion. For shallow, ice-covered, winter-kill lakes, loss of stream connections can eliminate access of seasonal migrants such as northern pike to adjacent deeper lakes during the winter. Loss of access would eliminate pike from shallow-lake assemblages, and the assemblage would shift toward species more tolerant of low oxygen and intolerant to northern pike predation (Lodge, 1993).

Large water-level changes characteristic of inland waters (Section 10.5.2; Figure 10-4), especially when exacerbated by climate change, have costly effects on urban and agricultural coastlines.

In 1986, agricultural and residential lands surrounding Lake Titicaca became inundated. At the highest water levels, people living in river valleys adjacent to the lake had to move upslope and switch their transport from connecting roads to boats. When the waters receded, the lower elevations began to be used only for agricultural purposes. The costs to adapt to future changes in water levels are $120 million for the first 5 years, based on a plan developed with the help of the European Community (Autoridad Binacional Autonoma de la Cuenca del Sistema TDPS, 1994). For Lake Michigan, bluff erosion during storms at high water results in property loss that includes destruction of residential and other shoreline developments. An extensive study concludes that the cost of controlling water level on all five Laurentian Great Lakes would be prohibitively expensive. Costs associated with adaptation to 2 x CO_2 water-level scenarios also are high. Changnon *et al*. (1989) estimate that increased dredging of harbors for a rather small length of Lake Michigan shoreline, including Chicago, would cost $138 to $312 million if water levels dropped by 1.25 to 2.5 m. Measures such as lowering docks, extending water supply sources and stormwater outfalls added another $132 to $228 million.

These examples demonstrate that water-level fluctuations at present and from climate-change scenarios can be large for lakes. Adaptation to, rather than control of, such large changes appears to be a common historical result in widely different settings and cultures. Such changes challenge the ability of human and natural communities to adapt and, in some cases, may be prohibitively expensive (see Chapter 12).

10.6.3. Species Distributions and Biodiversity

With climate warming, the poleward movement of freshwater communities will be at least as dramatic as the poleward movements of terrestrial vegetation (see Chapter 1). Extinctions and extirpations (local extinctions of species found elsewhere) will occur at the lower latitude boundaries of species distributions; where possible, poleward migrations will occur at the higher latitude boundaries of species distributions. Within geographic ranges, cool- and cold-water assemblages will be reduced in many rivers and shallow, unstratified lakes and ponds; suitable thermal habitat in many deep, stratified lakes will increase for warm-, cool-, and even cold-water organisms (see also Chapter 16).

Biodiversity increases from high to low latitudes (for fish, see Nelson, 1984; for streams, see Allan and Flecker, 1993). One might think that climatic warming, with adequate time, would increase the species diversity of many groups of organisms in mid- and high latitudes. In North America, species densities of fish in quadrates 1° latitude by 1° longitude are better correlated with the climatic factors of the quadrates than with the latitude or longitude of the quadrates (Hocutt and Wiley, 1985). Species density increased with temperature and decreased with aridity, but temperature and aridity together accounted for only 38% of the variation in species density. These general associations for large regions provide little information about the decade to century influences of climate warming on the biodiversity of individual waters. Interaction with more local conditions and local species distributions will be more informative.

10.6.3.1. Edges of Geographic Ranges

Species extinctions and extirpations will occur at the lower latitude boundaries of distributions if summer temperatures increase in streams and shallow, unstratified lakes and ponds and cooler-water refuges are not available. In the southern Great Plains of the United States, summer water temperatures of 38–40°C already approach the lethal limits (less than 40°C) for many native stream fish, most of which are minnows (Matthews and Zimmerman, 1990). Fish aggregate in slightly cooler shaded waters of pools and tributary streams (32–35°C); this crowding induces various stresses, including overexploitation of prey resources. These wide, slow-moving streams have no high-altitude refuges; they flow to the south or east, making escape poleward unlikely. If a 3–4°C warming occurs, many endemic species could become extinct.

Biogeographic distributions of aquatic insects are centered around species' thermal optima (Vannote and Sweeney, 1980). Climatic warming would shift the optimum temperatures poleward and eliminate species near their lower latitude limits. In North America, a 4°C warming is projected to shift stream thermal regimes—and potentially the center of species distributions—about 640 km northward (Sweeney *et al*., 1992).

At the higher latitude boundaries of species' distributions, organisms should be able to migrate poleward with climate warming, provided the new habitats are accessible through connecting waters. In North America, a 4°C increase in air temperatures is sufficient to move the simulated ranges of smallmouth bass and yellow perch northward across Canada by about 5° latitude, or about 500 km (Shuter and Post, 1990). These simulations include the entire life cycles and seasonality in both thermal and biological models.

10.6.3.2. Within Geographic Ranges

With projected climatic warming, stream fish habitats are predicted to decline across the entire United States by 47% for cold-water, 50% for cool-water, and 14% for warm-water species, independent of influences from other climate-related changes such as reduced stream flow (Eaton and Scheller, 1996). Only a few warm-water fish—bluegill, largemouth bass, channel catfish (*Ictalurus punctatus*), and common carp (*Cyprinus carpio*)—increase markedly in these simulations (Figure 10-8). These simulations assume that waters mix from

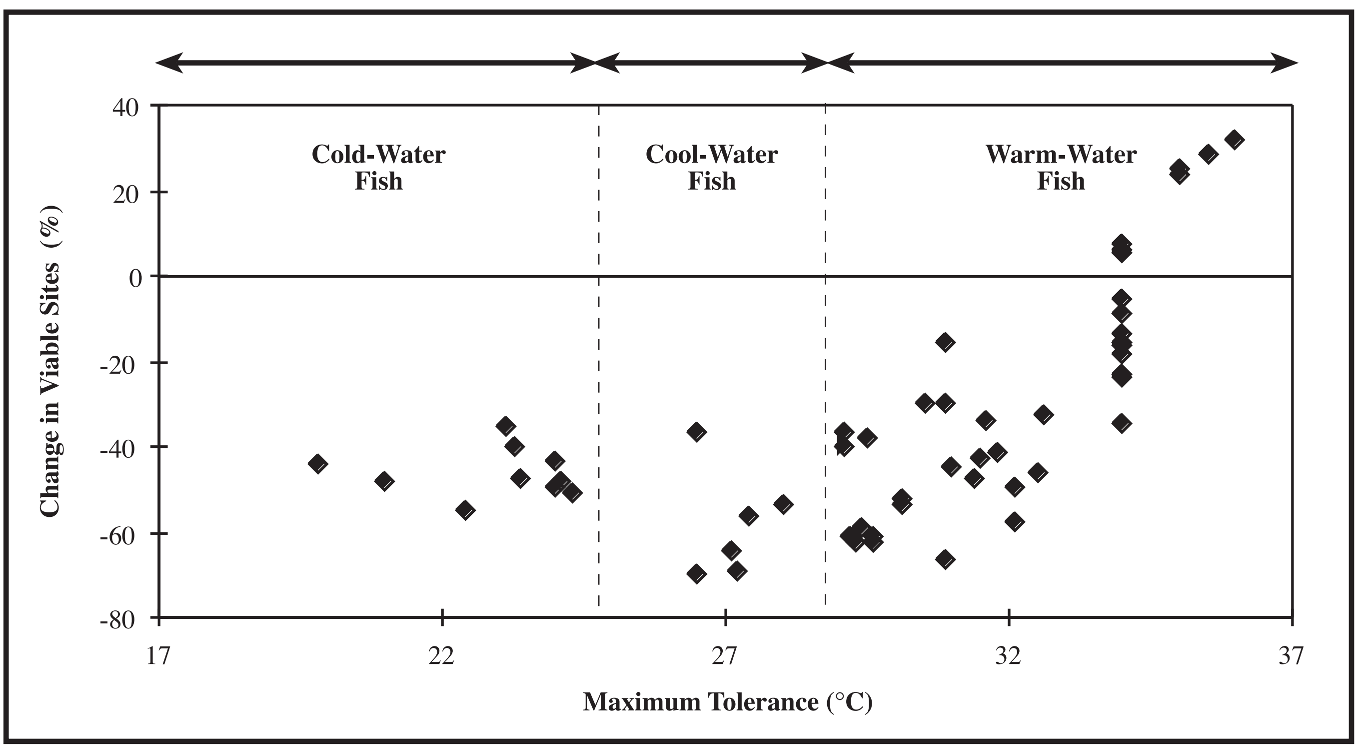

Figure 10-8: Changes in percentage of sites suitable for cold-, cool-, and warm-water fish at 1,700 U.S. Geological Survey stream sites across the United States, under a CCC GCM 2 x CO_2 scenario. Each point is a species plotted against its maximum thermal tolerance. Analysis and definitions are from Eaton and Scheller (1996).

surface to bottom and local thermal refuges do not exist. Scenarios are derived from air-temperature simulations across the United States with a 2 x CO_2 climate and a 0.9 factor to convert air to stream temperatures.

Heterogeneous thermal habitats can provide thermal refuges. In laboratory gradients, most freshwater fish spend two-thirds of their time within a 4°C range and all of their time within a 10°C range around their preferred optima (Magnuson *et al*., 1979; Magnuson and DeStasio, 1996). This ability allows them to seek out survivable or optimum temperatures in lakes and streams that are thermally heterogeneous. In summer, stream fish can move to higher elevations (Rahel *et al*., 1996), to reaches closer to groundwater sources (Meisner, 1990), or to shaded cooler areas (Matthews and Zimmerman, 1990); in thermally stratified lakes, fish can move downward to deeper, cooler waters (Magnuson and DeStasio, 1996).

In mountain streams of Wyoming, habitat loss is predicted for cold-water fish even with small increases in temperature (Rahel *et al*., 1996). An increase of 1°C reduces stream habitat for cold-water fishes by 7–16%, 2°C by 15–26%, 3°C by 24–39%, 4°C by 42–54% and 5°C by 64–79%. Remaining enclaves of cold-water fish would exist as smaller fragmented populations, with an increased probability of extinction from ecological disturbances such as fire or drought (Allendorf and Waples, 1987; Mills and Smouse, 1994).

Biotic interactions for stream invertebrates also intensify as flows decline or streams dry; mobile organisms are concentrated into smaller areas, resulting in intense predation and competition and potentially a loss of some taxa and diversity (Carpenter *et al*., 1992; Grimm, 1993).

In deep, thermally stratified temperate lakes, thermal habitat generally increases with 2 x CO_2 scenarios of global warming, not only for warm- and cool-water fish, but also for cold-water fish (Magnuson *et al*., 1990; DeStasio *et al*., 1996; Magnuson and DeStasio, 1996) (Figure 10-9). Similar increases are projected in smaller and larger lakes in Wisconsin for warm- and cool-water fish, but results were equivocal among GCM scenarios for cold-water fish in the smaller lakes. Increases occurred because the length of the growing season increased and because fish could move to deeper, cooler waters when surface waters exceeded preferred temperatures. Deep-water thermal refuges for cold-water fish are maintained in model projections over large latitudinal ranges (McLain *et al*., 1994), assuming that deep-water oxygen is sufficient.

Changes in deep-water oxygen and other habitat variables may prevent cold-water fish from occupying their thermal niches in a warmer and drier climate (Magnuson and DeStasio, 1996). Increases in water clarity can deepen the thermocline of small lakes, so that deep cold waters are significantly reduced in size (see Sections 10.5.3 and 10.5.4 and Box 10-2), and dissolved oxygen may be reduced in deep waters (see Section 10.5.4 and

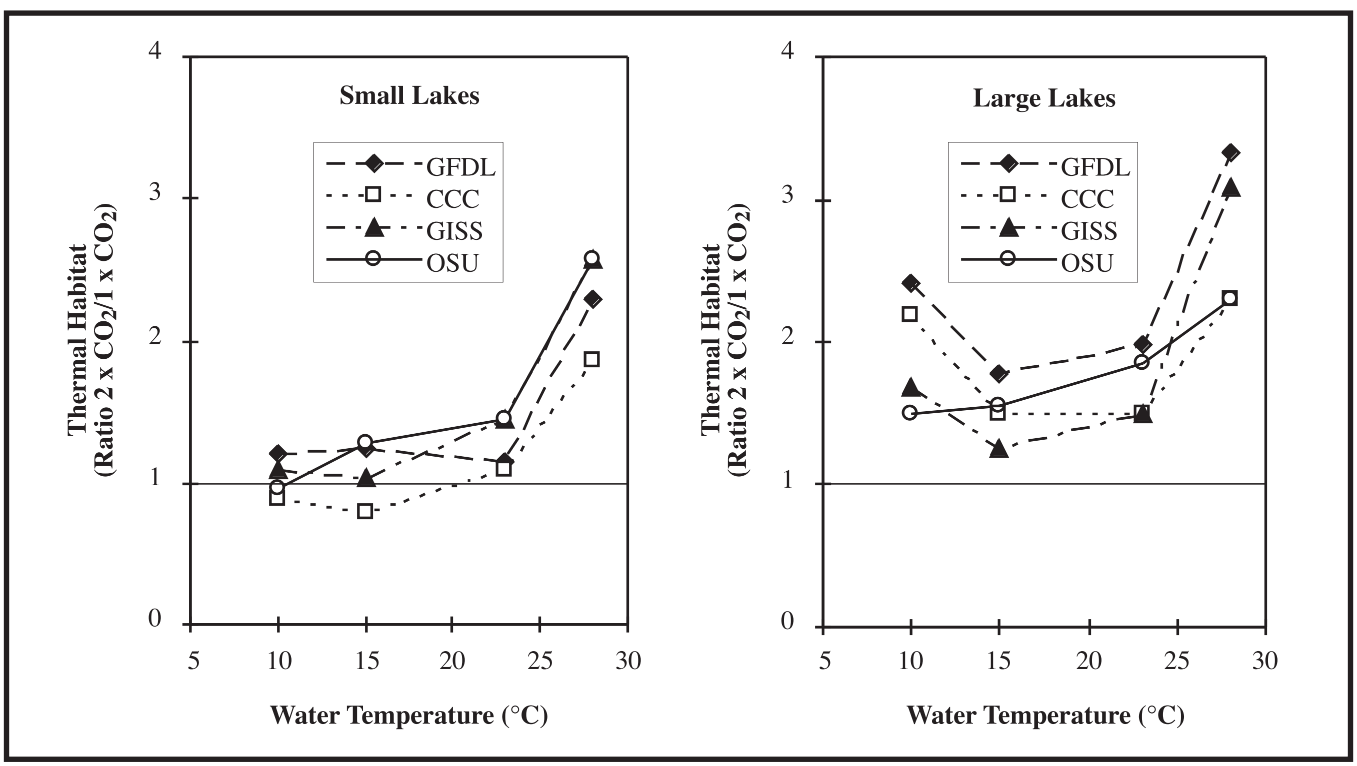

Figure 10-9: Simulated changes in thermal habitat in small (Crystal and Sparkling) and large (Michigan, Mendota, and Trout) stratified temperate lakes for cold- (10 and 15°C), cool- (23°C), and warm-water (28°C) fish under a 2 x CO_2 climate with four GCMs (GFDL, CCC, GISS, and OSU), as modified from Magnuson and DeStasio (1996).

Figure 10-7). Other relevant analyses exist for northern pike in impoundments (Headrick and Carline, 1993), striped bass in reservoirs (Coutant, 1985, 1987), and anadromous salmon (Crawshaw and O'Connor, 1996).

10.6.3.3. Genetic Adaptation, Dispersal, and Invasions of Exotic Organisms

Rates of climate warming are likely to exceed rates of genetic adaptation for some local populations of aquatic invertebrates, as well as the rate of natural dispersal of warm-tolerant populations that might be expected to replace them (see Box 10-4). Similar projections can be made for fish. Genetic variation in critical and chronic thermal maxima has occurred in separated populations of largemouth bass (Fields *et al*., 1987), but thermal preference has not changed among populations (Koppelman *et al*., 1988). Crawshaw and O'Connor (1996) speculate—from mammalian studies and similarities between fish and mammal thermoregulatory anatomy and processes—that genetic shifts in thermal preferences of fish might be fast under certain conditions.

The lack of suitable north–south migration routes (drainages) may limit dispersal, as well as replacement of cold-water fauna with warmer-water fauna. If dispersal rates of arriving warm-water species are low in freshwaters with declining cold-water taxa, the biomass and productivity of the community would be reduced with climate warming, at least initially, because range shifts may lag behind changes in thermal regimes (for stream invertebrates, see Sweeney *et al*., 1992). This problem would be most restrictive for taxa that are less vagil (e.g., aquatic insects with fragile or short-lived adult stages) and for isolated freshwater ecosystems such as closed-basin lakes and streams. Isolation would be less severe for organisms that can be carried by the wind, such as very small organisms (e.g., algae and microbes) and those with small resting stages (e.g., cladocerans and rotifers), or for organisms with flying adults such as many aquatic insects. Fish dispersal (Magnuson *et al*., 1989b; Tonn *et al*., 1990) would be more restricted to water courses, transport by humans, or even rare extreme events (Dennis and Wolff, 1992) such as tornadoes.

Dispersing organisms arriving for the first time in a new ecosystem are exotic (new) to that system. Such invading species often interact with existing species in unexpected ways. Invasions of exotics can disturb the existing community structure and the productivity of species of value to humans. Rates of species invasion would increase poleward as conditions warm (Mandrak, 1989). These invasions can hasten changes associated with climate warming by increasing the rate of decline of existing species (Lodge, 1993) and add to the uncertainty (Magnuson, 1976) of predicting the effects of climate warming.

10.6.3.4. Observed Changes in Biodiversity

Box 10-4. Genetic Response to Warming

Genetic variability in mayflies of eastern North America decreases to the north; thus, populations for which global warming may be most pronounced are least-equipped genetically to adapt (Sweeney *et al*., 1992). Many species of mayflies are weak dispersers and may be unable to move rapidly enough to keep up with poleward migration of isotherms (Sweeney *et al*., 1992). Increasing temperatures and associated ecological changes may tax their ability to adapt.

Some aquatic invertebrates show high genotypic variability with little differentiation among sites; others vary greatly among sites but exhibit little genetic variability within a site. Hogg *et al*. (1995) tested the hypothesis that populations with little genetic variability would fare less well in a changing environment than those with more genetic variability. The amphipod *Hyalella azteca* disperses poorly but has high genetic variation; a stonefly, *Nemoura trispinosa*, has flying adults but low genetic variation. On one side of a split southern Ontario stream, temperature was raised year-round by 2.0–3.5°C for 3 years. Total invertebrate fauna was reduced by this treatment, but neither *H. azteca* nor *N. trispinosa* declined, although they did show life-history changes. Under warm conditions, the amphipod bred two months earlier and the stonefly emerged two weeks earlier at slightly smaller sizes. The authors postulate that endemic populations with poor dispersal abilities would suffer the long-term consequences of environmental warming.

Long-term observations as well as observed paleolimnological changes in organisms and in chemical conditions recorded in lake sediments can suggest the kinds of responses of freshwater biodiversity to future changes in climate.

Lake sediments accumulate over time and can contain an interpretable record of the history of the lake's biota from the remains of diatoms, chrysophytes, zooplankton and other aquatic invertebrates, and, rarely, even fish. A variety of organisms have been examined for use in inferring changes in climate; they explicitly indicate changes in lake biota in response to climate change. Diatoms appear to be the most sensitive indicators of past lake conditions; they are being used to examine the history of lakes in closed basins (Juggins *et al*., 1994) and water levels (Gont *et al*., 1988). They have been used to examine changes in the duration of ice cover (Smol, 1988). As a consequence of habitat specificity related to temperature (Douglas and Smol, 1995), they may be sensitive indicators of increases in temperature, especially in the high Arctic. Diatom communities respond to changes in salinity (Fritz *et al*., 1993) that result from changes in precipitation or runoff. Diatoms respond to a number of environmental conditions, and they are sensitive to light and nutrient availability (Kilham *et al*., 1996).

Diatoms and chrysophytes have been especially responsive to past changes in climate and climate-induced changes in water chemistry (Battarbee *et al*., 1990; Bradbury and Dean, 1993; Cumming *et al*., 1993; Davis *et al*., 1994; Smol and Dixit, 1990).

In natural thermal gradients of streams and in experimental streamside channels, the total number of algal species increases with temperature up to 25–30°C, then declines above 30°C as many diatom species are replaced by fewer species of green algae and cyanobacteria (Patrick, 1971; Squires *et al*., 1979; Lamberti and Resh, 1983). Phytoplankton biodiversity increased slightly over a 20-year period of warmer and drier weather in a Canadian Shield lake (Schindler *et al*., 1990).

The greatest biodiversity is expected at intermediate disturbance regimes; thus, large increases or reductions in flood frequency or size in streams (Ward and Stanford, 1983; Reice, 1994) or severity of winter kill in lakes (Tonn and Magnuson, 1982) can alter diversity. Analyses of streams in Wisconsin and Minnesota and in New Zealand indicate that fish communities are simpler and comprise more generalist species in streams with more-variable hydrologic regimes (Poff and Allan, 1995; Jowett and Duncan, 1990).

Increases in the frequency or severity of droughts may affect biodiversity in streams more than increases in the size of flood events because droughts result in longer-term habitat loss. Sharp reductions in the diversity of stream invertebrates followed dry years in arid streams of Arizona (Stanley and Fisher, 1992) and Australia (Boulton *et al*., 1992). Even if streams do not become intermittent, extended periods of low flow would reduce the diversity of organisms intolerant of reduced water quality (Chessman and Robinson, 1987; Boulton and Lake, 1990). Despite short-term reductions in densities and biomass, floods do reduce predation pressure and lessen competition and thus can increase species diversity (Dudgeon, 1993; Grimm, 1993).

10.6.4. Adaptations to Changes in Climate

10.6.4.1. Land Use: Catchment, Riparian/Flood Plain

In smaller streams and rivers, augmentation and protection of riparian vegetation will provide shade and reduce the negative effects of warming. For the north-central United States, Stefan and Sinokrot (1993) estimate that the predicted summer rise in stream temperature will be 6°C higher if streamside vegetation is lost. In the southern United States, the rise in summer stream temperatures is primarily from increased radiation; predicted summer increases in water temperature can be reduced by at least 50% in the more humid regions with more riparian vegetation (Cooter and Cooter, 1990).

10.6.4.2. Hydrological Regime and Water Level

Maintenance of existing flood plains and flood plain-river exchanges or restoration by removing barriers such as levees may help in some cases to detain water during flood events, reducing flood peaks in downstream areas. Flood plains are vital to reducing flow variability and flood peaks in river basins.

Restoration of river and stream channels to more-natural morphologies would mitigate some negative effects of climatic drying and reduced flows. Natural morphologic features such as meanders and variable channel topography with deeper pools provide temporary refuges for organisms intolerant of reduced water depths or streambed drying. Permanent pools are critical refuges for many species when flow ceases in intermittent streams (Williams and Hynes, 1977; Boulton and Lake, 1992).

The already large water-level changes of lakes will be exacerbated and in most regions will be in the direction of lower levels. Shoreline structures and facilities, water intakes, and waste discharge will need to be extended or rebuilt. Human populations in most cases will begin to use the newly exposed lands for agriculture, habitation, and recreation and will have to retreat when water levels rise—with loss of property uses and values (see Chapter 12).

10.6.4.3. Heat-Loading Interactions with Nutrient and Toxic Wastes

Climate changes that produce higher water temperatures and lower flows and water levels will increase the negative effects of wastewater and thermal effluents on freshwater ecosystems. Because warmer temperatures make lakes and streams more productive—in a sense, more eutrophic in their behavior—it may be necessary to reduce alternate causes related to unwanted or nuisance production. Among the options would be to further decrease the loading of nutrients such as phosphorus and nitrogen from sewage treatment plants or to reduce leakage from diffuse agricultural and urban sources. Human adaptations that reduce these effluents—such as recycling or land application of wastewater effluents where appropriate—and increased use of recirculating cooling systems with cooling towers could help. Because the accumulation of many toxic substances in the freshwater food web is greater at higher temperatures, it also may be necessary to further reduce the release of these contaminants or further constrain the ingestion of contaminated fish by humans.

10.6.4.4. Biological Management: Harvest, Removals, Introductions

Zoogeographic responses to the loss of livable habitat at lower latitudes and gains in livable habitat poleward could be assisted by moving organisms poleward where warranted. Although this might save species that are about to be extirpated or go extinct at lower latitudes and expand the ranges at higher latitudes into suitable habitat, the introduction of these species into new habitats will not necessarily be successful. Two problems can be anticipated. First, these species may not establish viable populations in many cases, and the species may be lost before the consequences of introductions become predictable. Second, if they do establish a population they may negatively impact existing species already under stress from climate warming or emigrate into other connected freshwaters and exert unwanted effects there. A common effect of introductions in freshwaters is the extinction of existing species. This also may have negative influences on existing uses of the freshwater ecosystem for fishing and other purposes that rely on water quality.

10.7. Research Needs

Further research is needed to reduce the level of uncertainty in hydrological and freshwater ecosystem impact assessments, focusing mainly on developing credible change scenarios. Specific areas requiring improvements follow:

- The accuracy of and reductions in the discrepancies between GCM simulations at the regional scale
- The understanding and modeling of land–atmosphere exchange processes at a range of spatial and temporal scales
- The understanding of the effects of CO_2 enrichment on plant water use in natural settings at the catchment scale
- Methods for defining credible scenarios for changes in weather patterns leading to flood and drought, including stochastic weather generators and nested regional climate modeling
- The understanding and modeling of hydrological systems under nonstationary climatic conditions, which involve the maintenance and enhancement of monitoring networks; the development of methods for the acquisition of spatially distributed estimates of state variables such as soil moisture, evapotranspiration, and infiltration by remote or inexpensive direct measurements; and the development of credible hydrological models with climate-invariant parameters
- The understanding of the effects of the El Nino/Southern Oscillation (ENSO) and other large-scale atmospheric features on hydrological characteristics, and the changes caused by global warming.

There is a need to reverse the decline in climatic, hydrological, and ecological monitoring networks and services in many countries, particularly coupled precipitation and streamflow monitoring in small catchments that provide whole-system indices of changes in evapotranspiration. Continuing decline will make the detection of climate change impossible in many parts of the world and prevent the production of credible hydrological scenarios.

Research needs in freshwater ecology related to climate change include approaches to a predictive understanding of long-term, slow changes and processes with time lags greater than one year that determine the regional and local behavior of land/water ecosystems. The most important general needs follow:

- Long-term research and monitoring of key physical, chemical, and ecological properties (particularly water temperature and mixing properties; concentrations of nutrients, carbon, and major ions; acid/base status; and populations of key organisms) and processes (e.g., primary production, organic matter decomposition)
- Comparative studies of populations or ecological processes across latitudinal and hydrologic gradients and system types
- Paleo studies using sedimentary records of climate-sensitive parameters aimed at a more complete integration of paleohydrology and paleoecology trends, patterns, and future expectations
- Whole-system experiments altering the thermal, hydrological, or mixing regimes in small lakes and streams, including whole catchments, or in large-scale mesocosms (e.g., lake enclosures, artificial stream channels) to determine the responses of organisms and processes to projected climate changes
- Testing whole-catchment and regional approaches to improve predictive understanding of integrated land/water systems.

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